

What is Magnetic Susceptibility Contrast?

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<http://www.amri.ninds.nih.gov/index.html>



Overview

- *What is magnetic susceptibility contrast?*
- *Observations at high field*
- *Interpretation*
- *Clinical Applications*

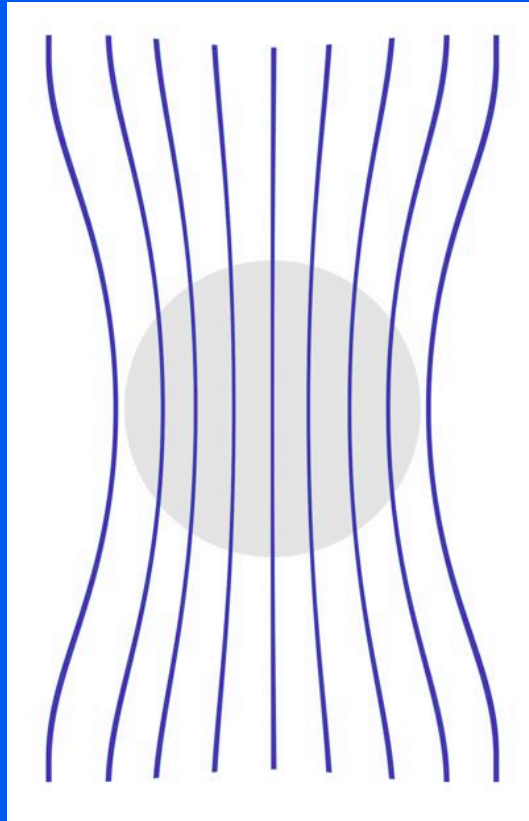
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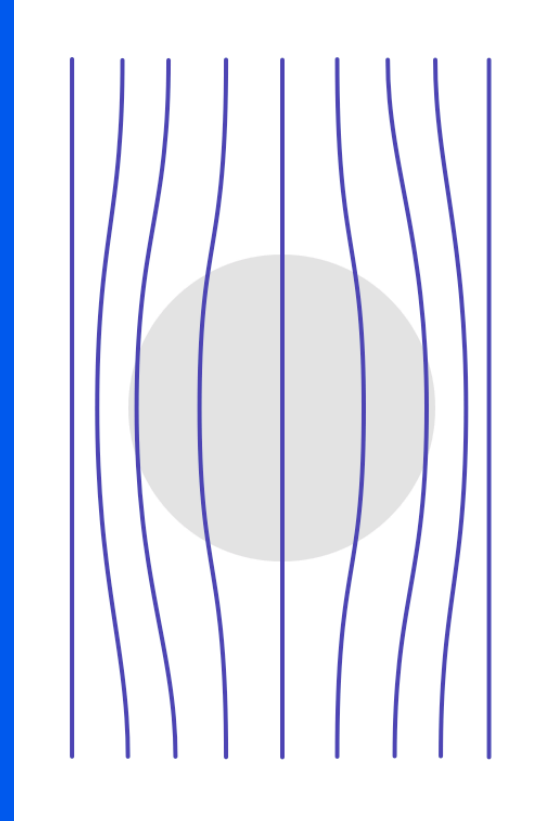
Magnetic Susceptibility = Magnetizability of Object



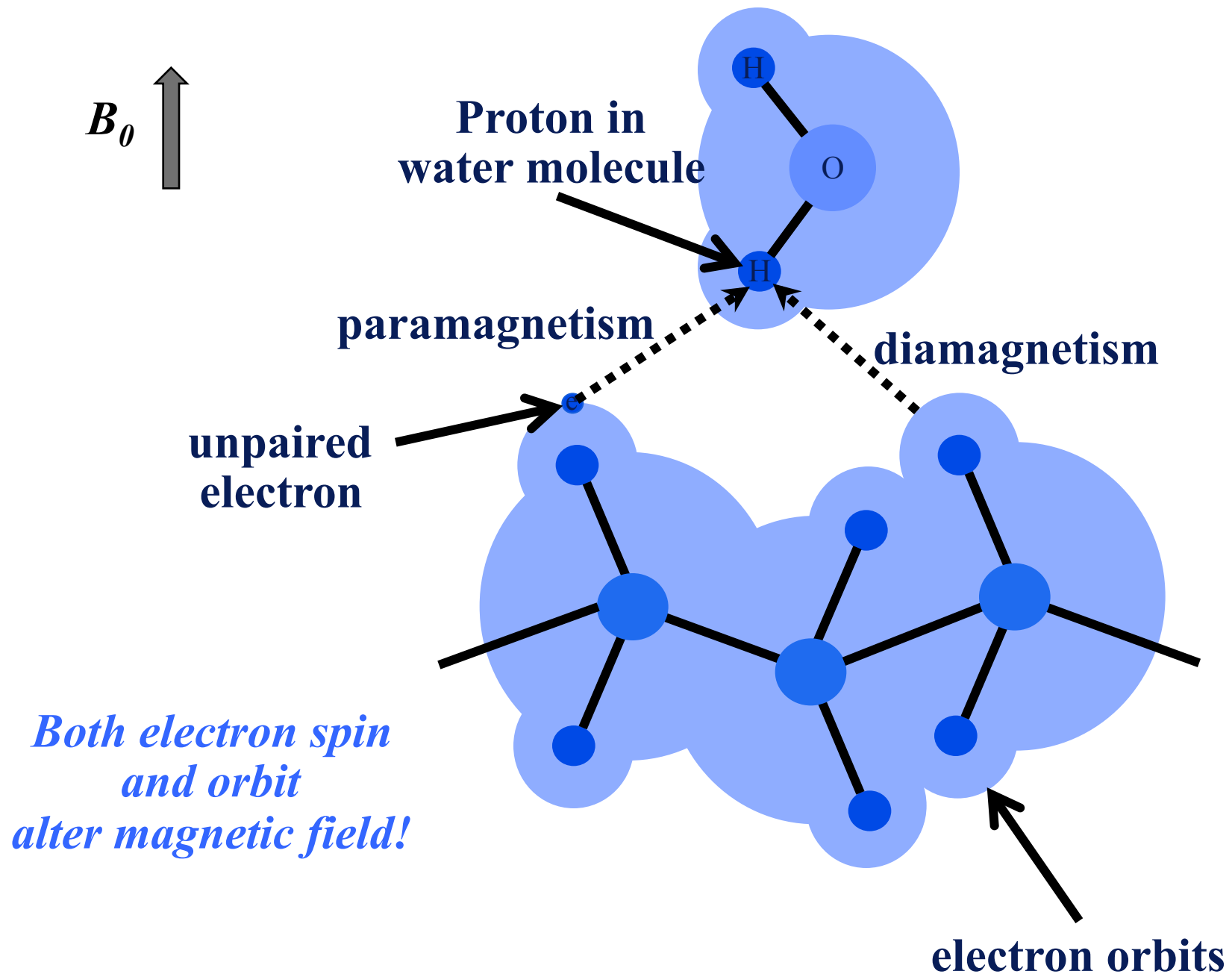
B_0



*Paramagnetism:
magnetization strengthens field*



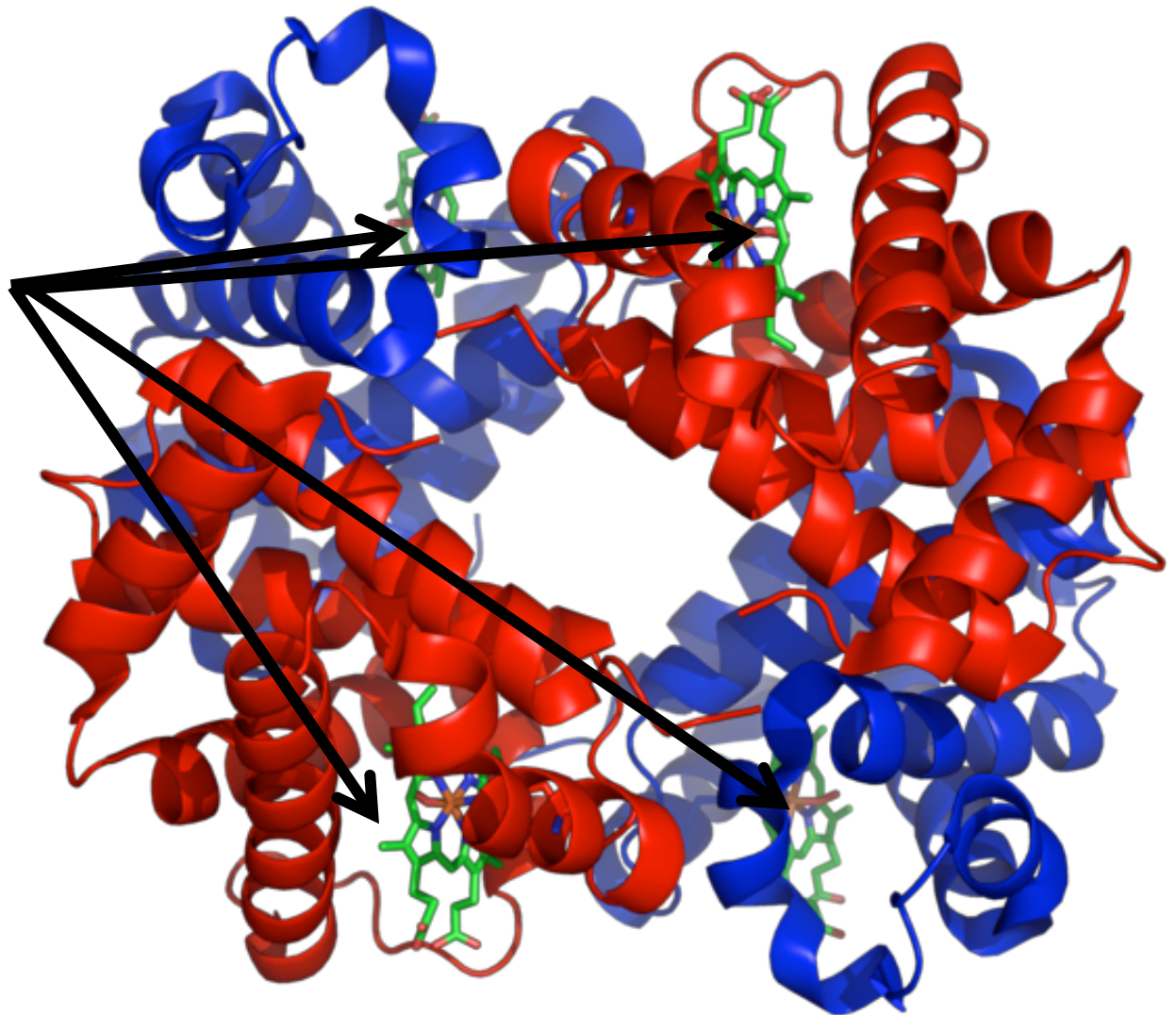
*Diamagnetism:
magnetization weakens field*



Deoxyhemoglobin

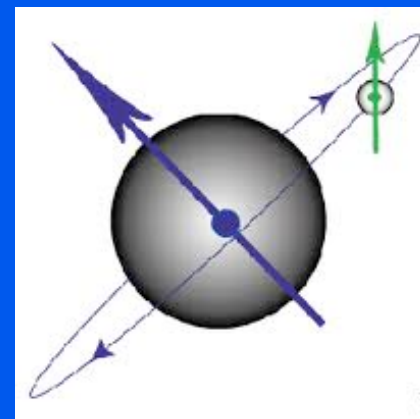
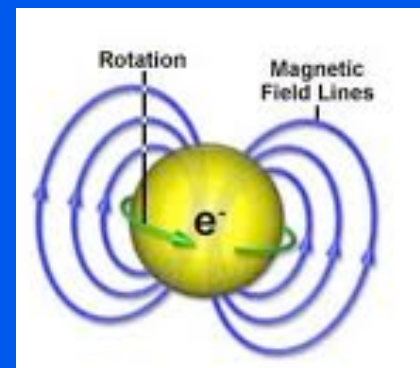
**4 irons
with 4 unpaired
electrons each:**

**strong
paramagnetism**



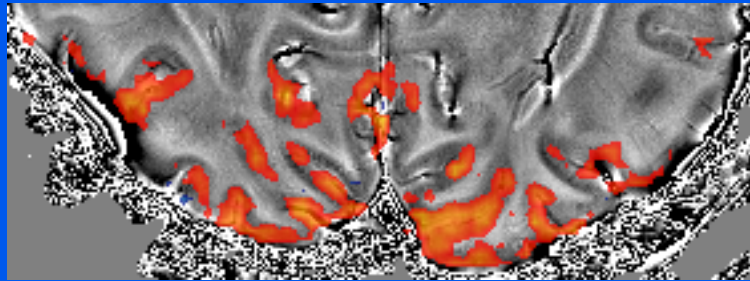
Sources and Mechanisms

| Sources | Type | Effect | Mechanism |
|--|--------------|------------------------------------|-----------------------|
| Iron/Ferritin, Deoxyhemoglobin, Gadolinium | paramagnetic | Magnetized <i>with</i> field | Unpaired electrons |
| Myelin | diamagnetic | Magnetized <i>against</i> field | Electron orbits |



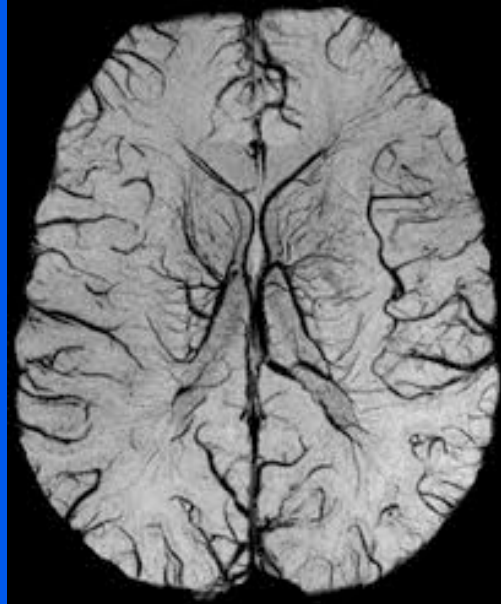
Magnetic Susceptibility Contrast

BOLD fMRI (~1992)

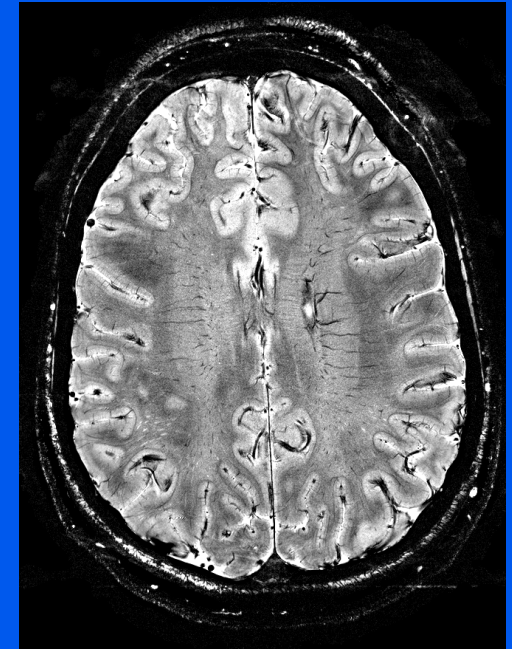


*Sensitivity to the
magnetic
properties of tissues*

**Venography
(~1998)**



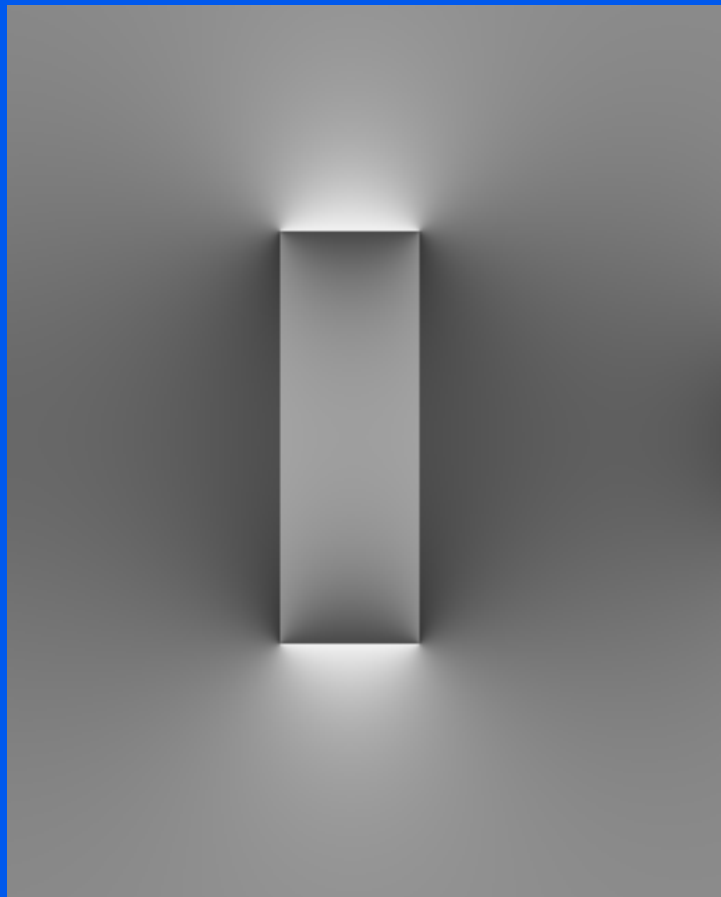
**General
Anatomy
(~2000)**



**magnetization alters field inside and outside
object**



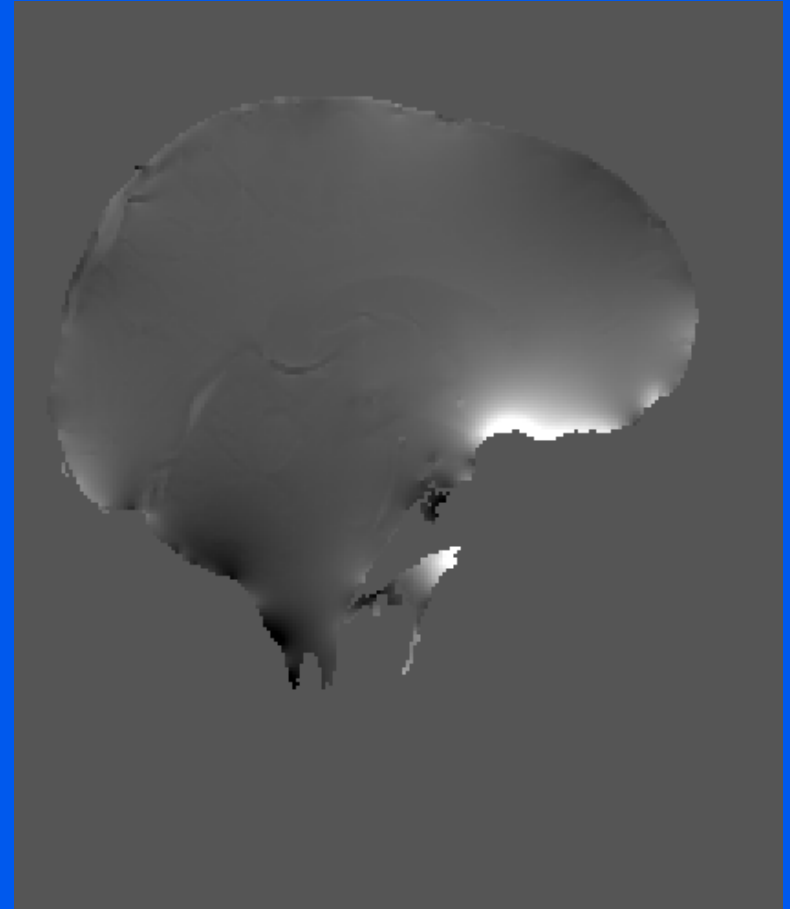
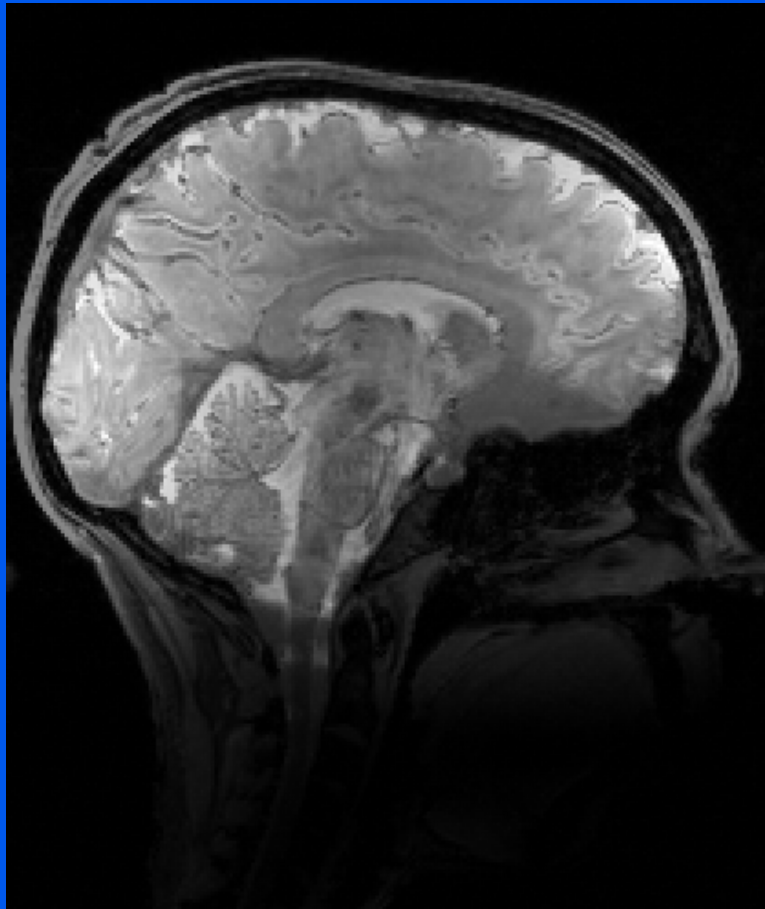
B_0



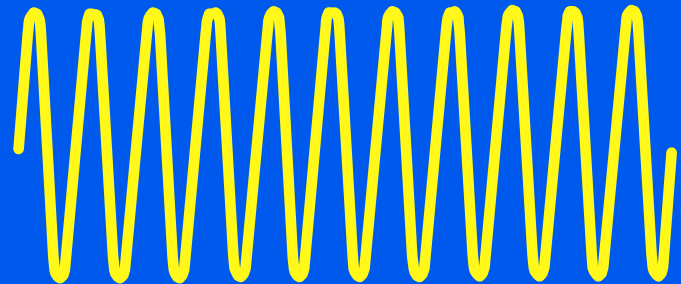
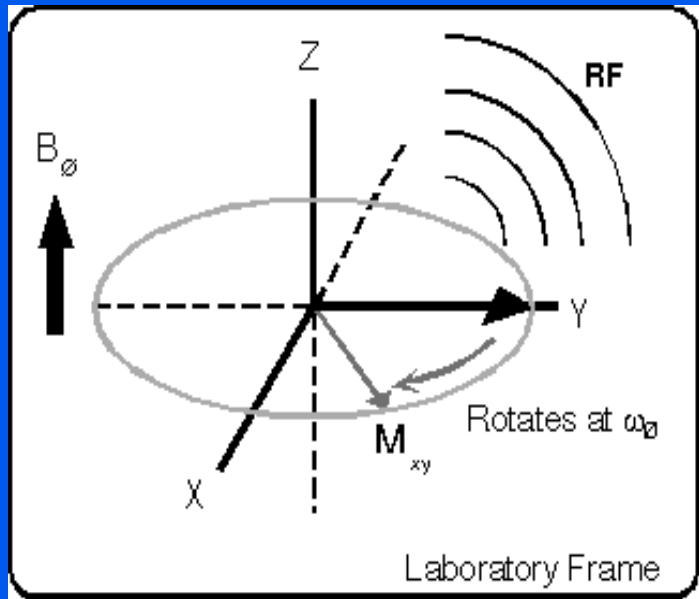
brain is diamagnetic and alters MRI field



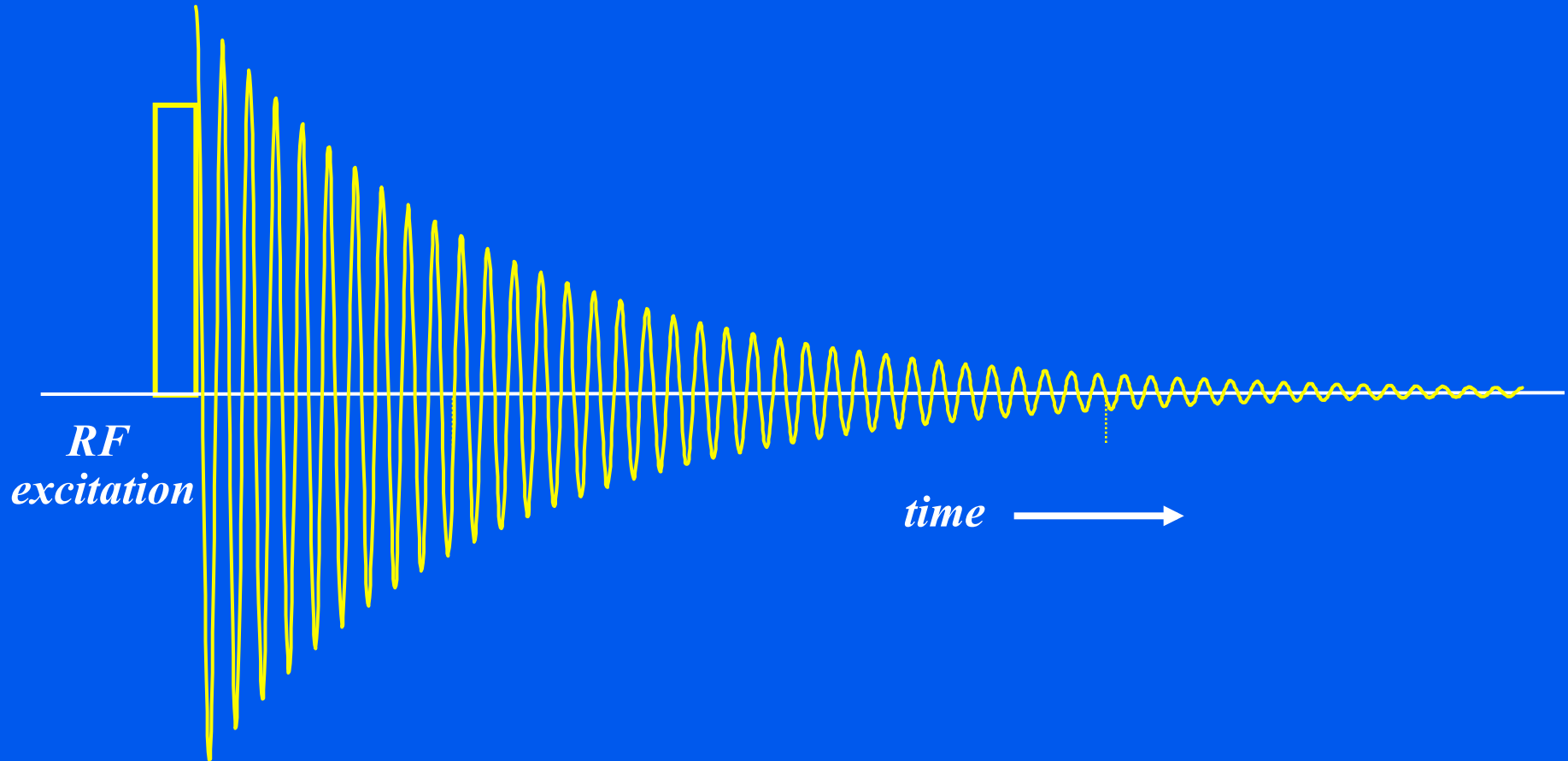
B_0



In NMR, field is sensed by proton spins through their precession frequency

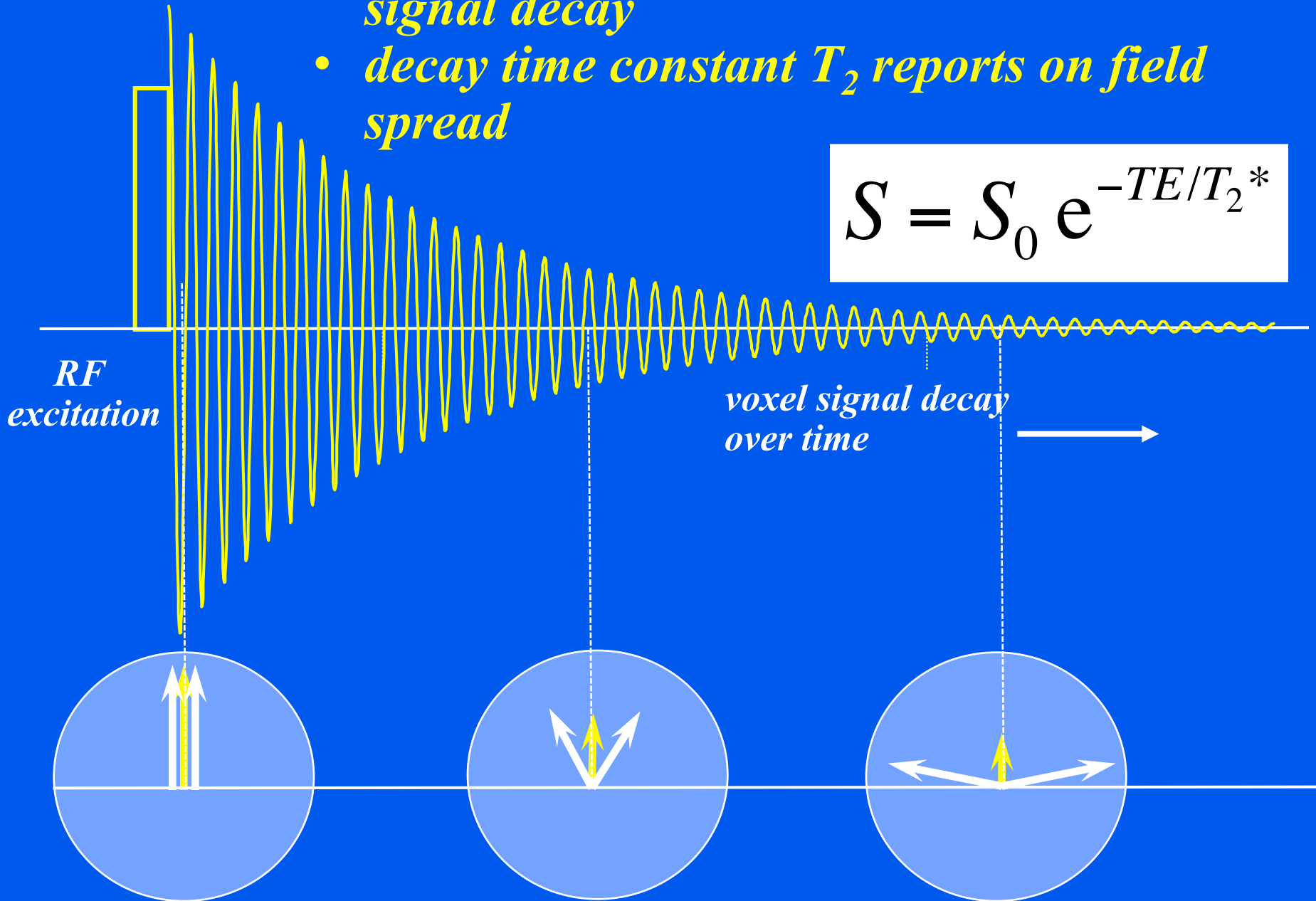


frequencies can be measured by observing signal decay after excitation

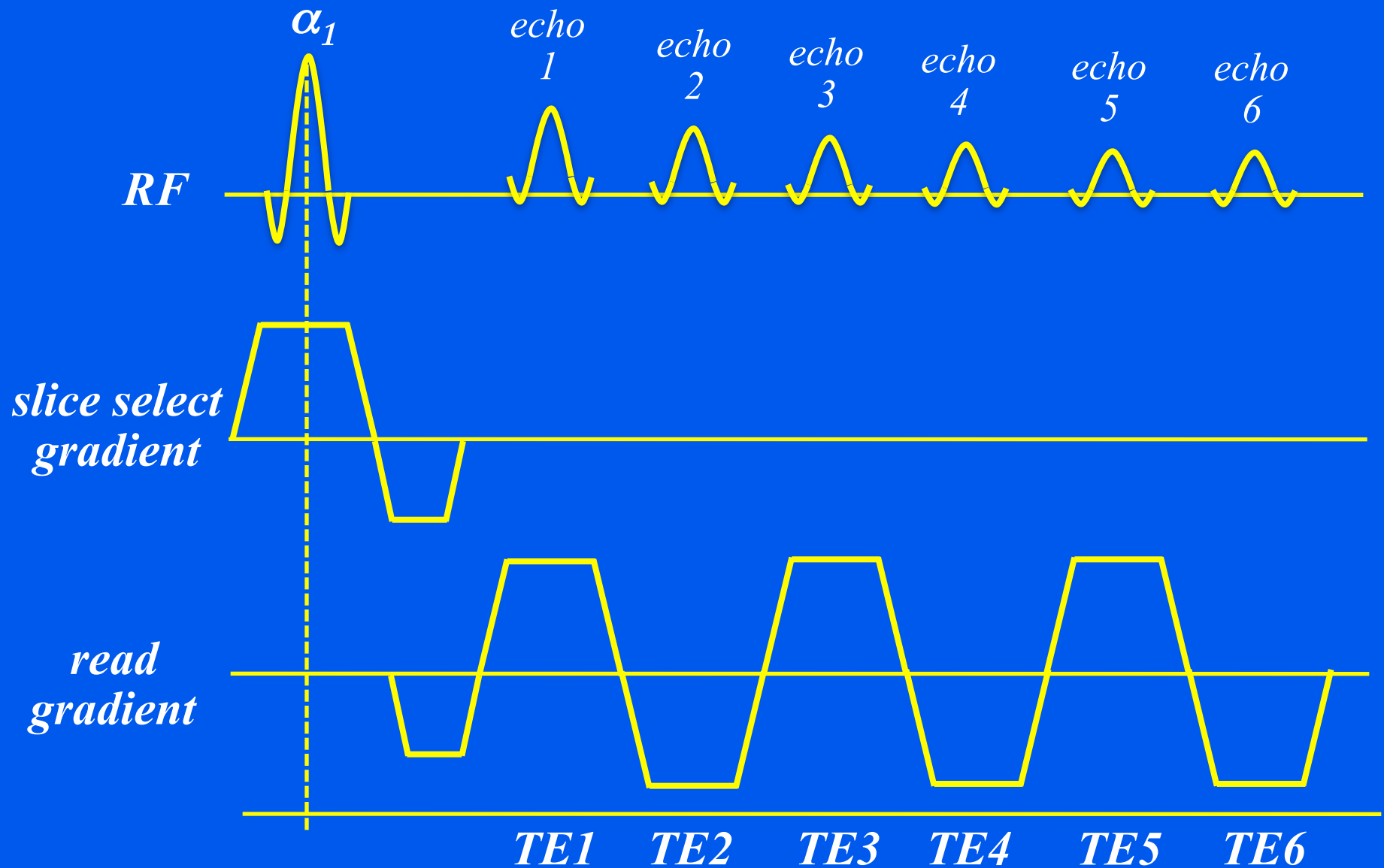


- *frequency spread within a voxel leads to signal decay*
- *decay time constant T_2 reports on field spread*

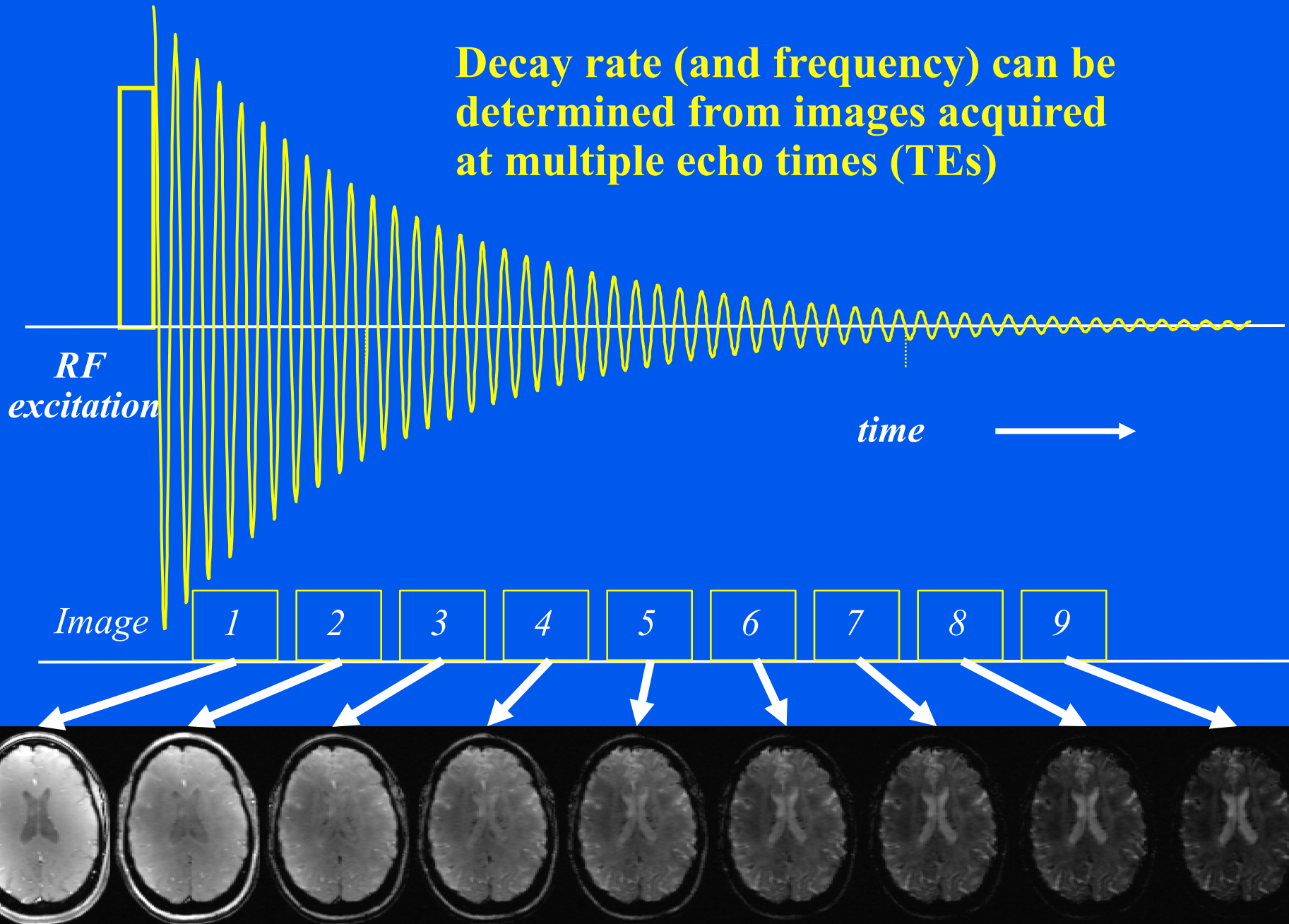
$$S = S_0 e^{-TE/T_2^*}$$



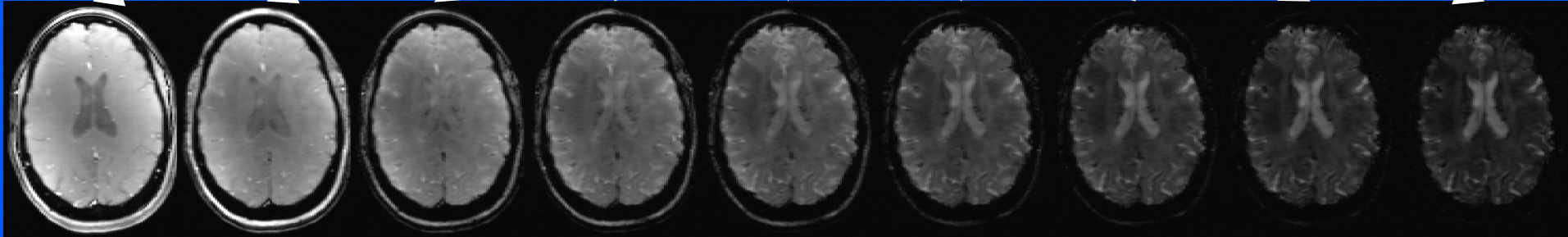
Multi-Gradient Echo MRI



Decay rate (and frequency) can be determined from images acquired at multiple echo times (TEs)



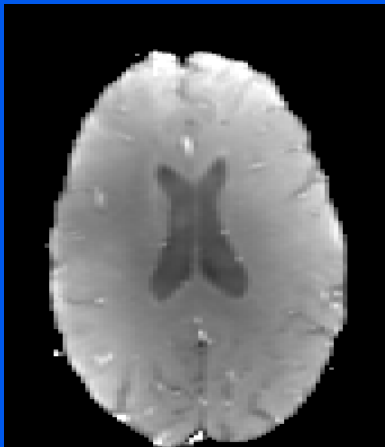
Magnitude
Images



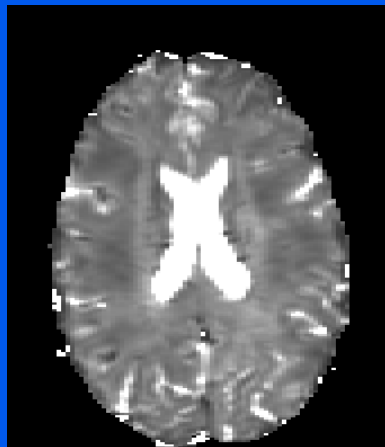
Fit:

$$S = S_0 e^{-TE/T_2^*}$$

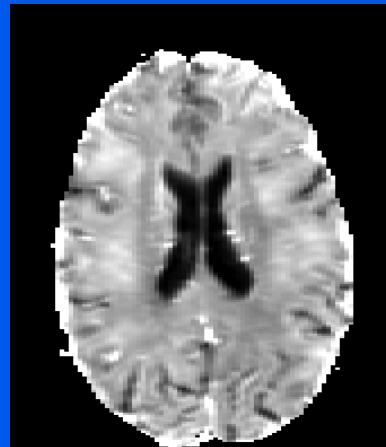
S_0



T_2^*



$R_2^* = 1/T_2^*$



extracted information

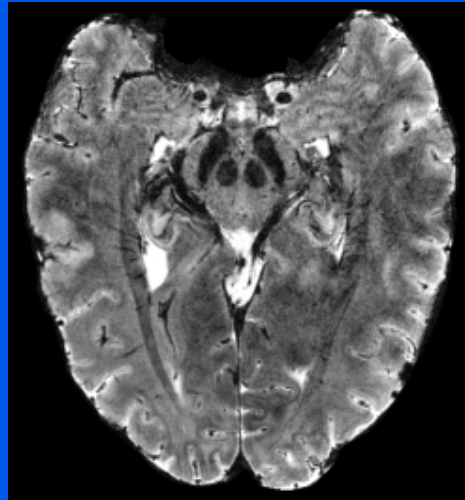
From magnitude images (at least two TE's):

- T_2^* -weighted images
- Spin density (M_0)
- T_2^* and R_2^*
- decay characteristics

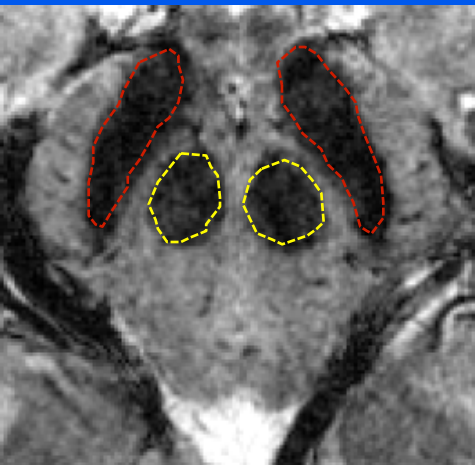
From phase image(s):

- frequency shift image
- reconstructed magnetic susceptibility;

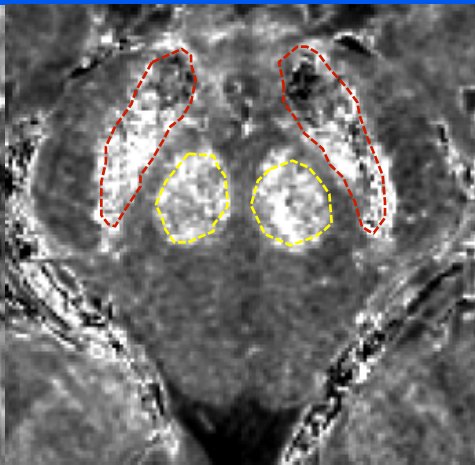
T_2^* -w magnitude



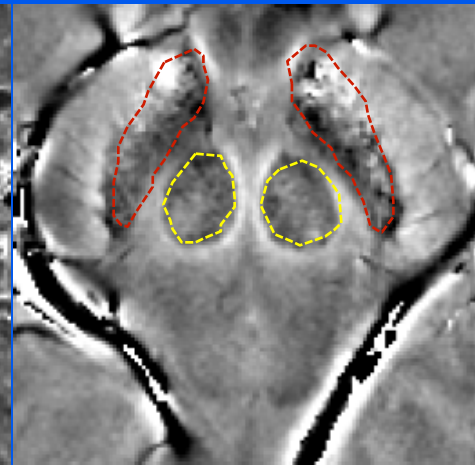
T_2^* -w
magnitude



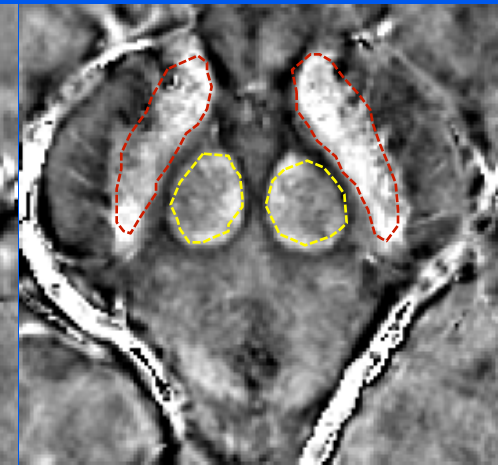
R_2^*



Frequency



Susceptibility



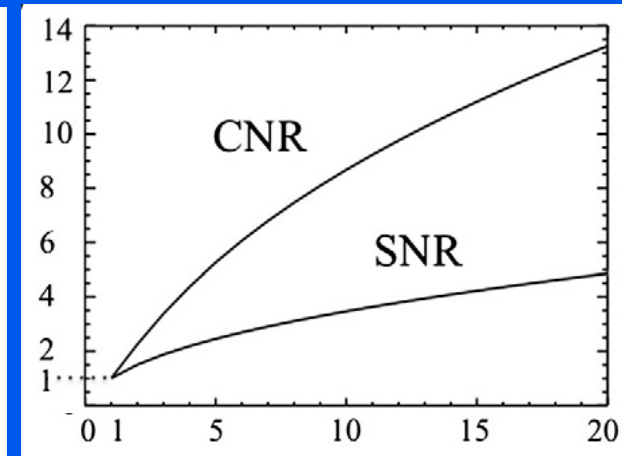
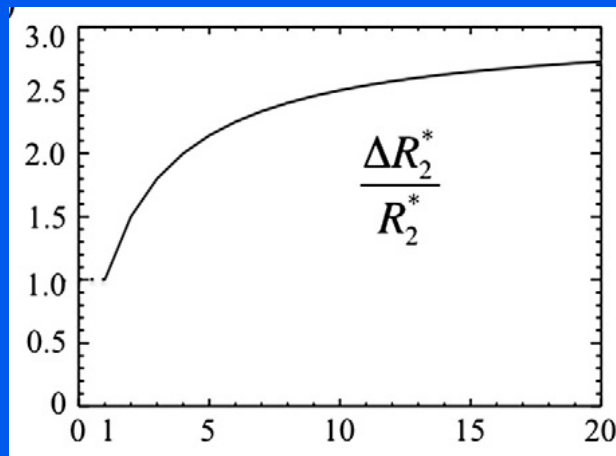
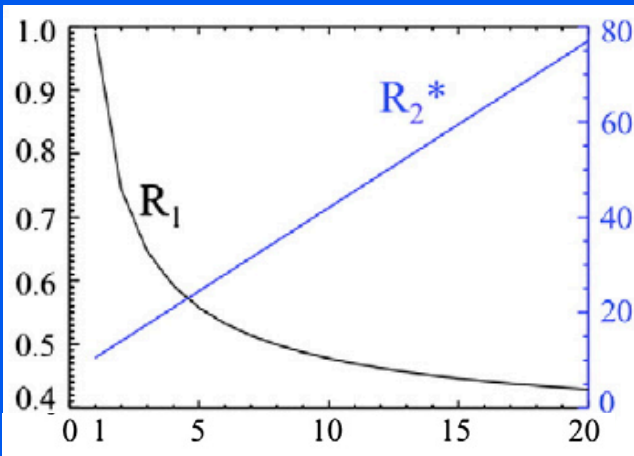
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High field: **Increased proton polarization (SNR)**
Increased magnetization (CNR)

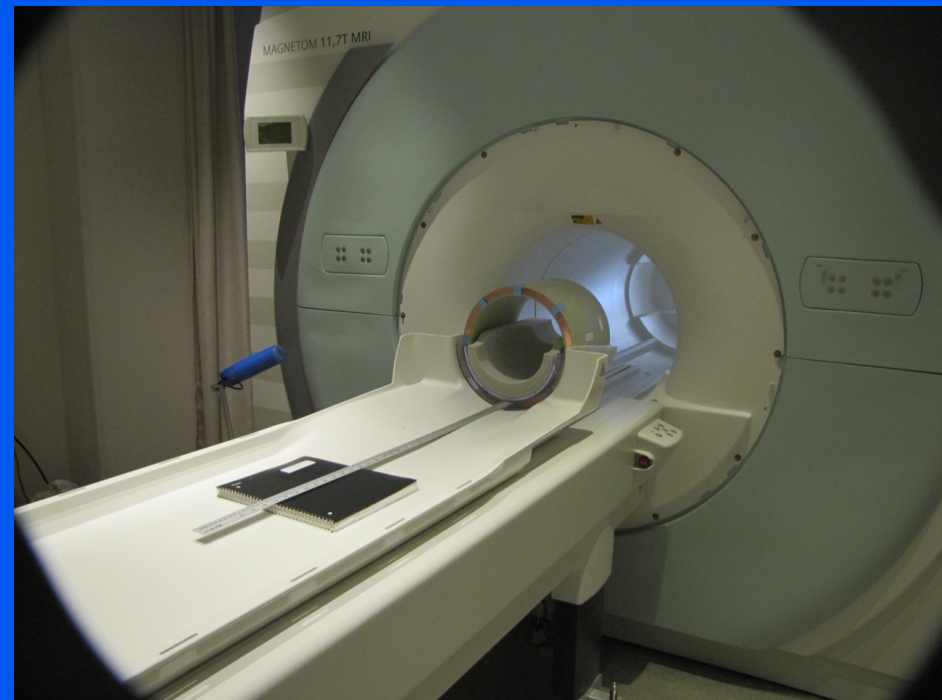
$$SNR \propto B_0 \cdot \sqrt{\frac{R_1}{R_2^*}}$$

$$CNR \propto B_0 \cdot \sqrt{\frac{R_1}{R_2^*}} \cdot \frac{\Delta R_2^*}{R_2^*}$$





7T shielded; November 2010



**11.7T head-only; November 2011
Currently under repair**

| magnet | 7T shielded | 9.4T | 10.5T Minnesota | 11.7T NIH (head) | 11.7T Orsay |
|--------------|-------------|------|-----------------|------------------|-------------|
| Bore ID (mm) | 830 | 900 | 880 | 680 | 900 |
| Diameter (m) | 2.4 | 3.0 | 3.2 | 2.7 | 5.0 |
| Length (m) | 2.9 | 3.7 | 4.1 | 3.7 | 5.2 |
| Weight (t) | 36 | 57 | 110 | 60 | 132 |



7T shielded

In use



9.4T

In use



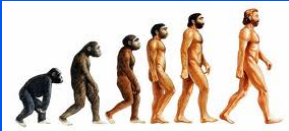
10.5T Minnesota

Near completion



11.7T NIH (head)

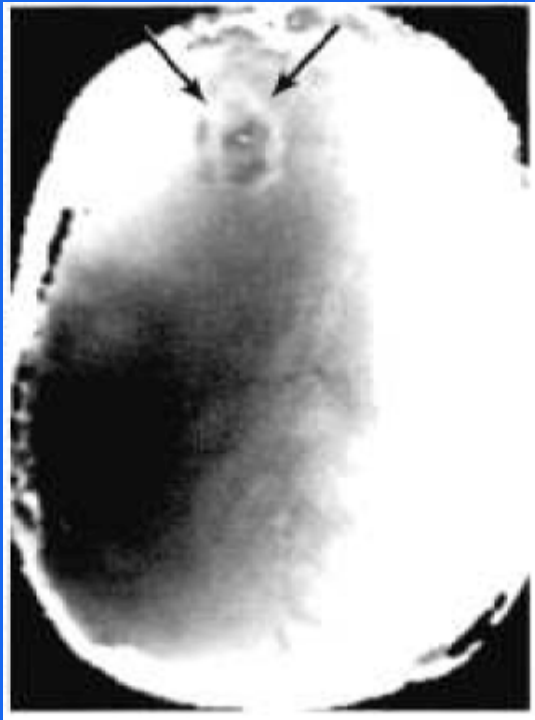
Under repair



11.7T Orsay

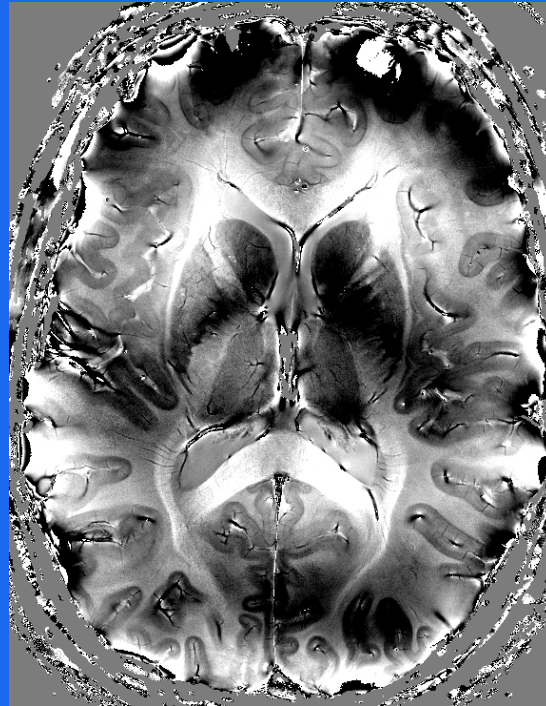
Under construction

0.15 T



Young/Bydder, JCAT1987

7 T



NIH, 2007

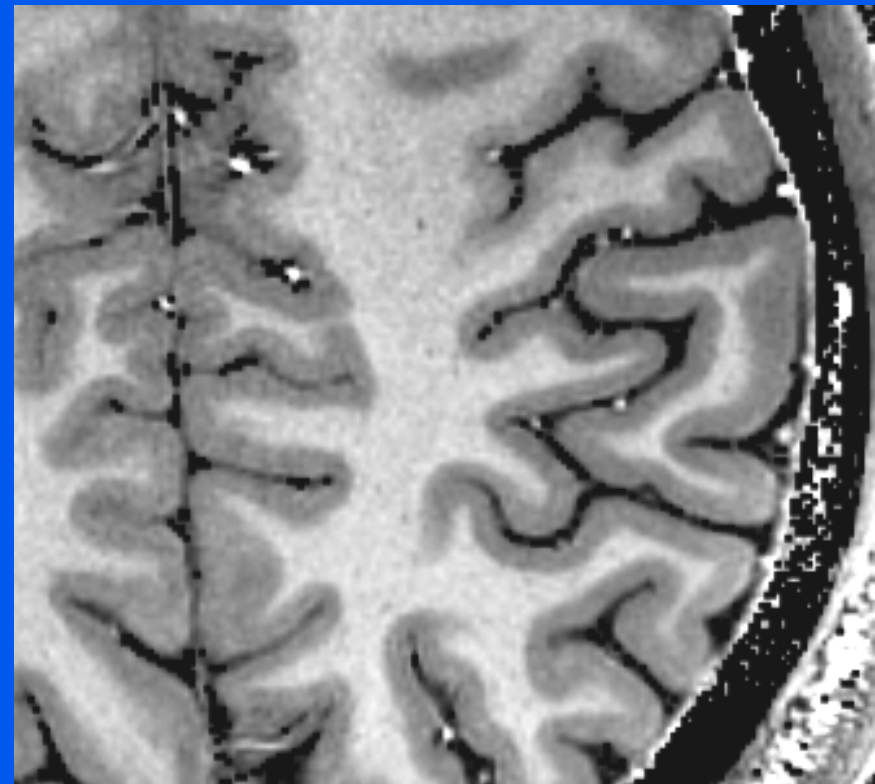
frequency contrast within grey and white matter

frequency

MPRAGE (T_1)

line of Gennari

optic radiation

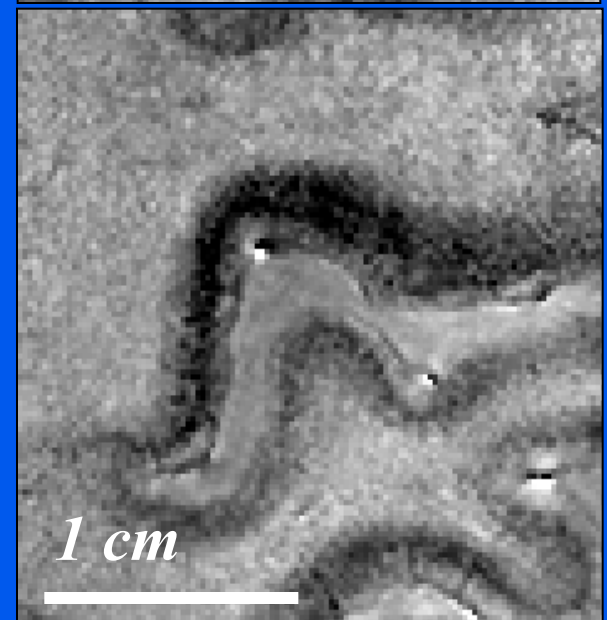
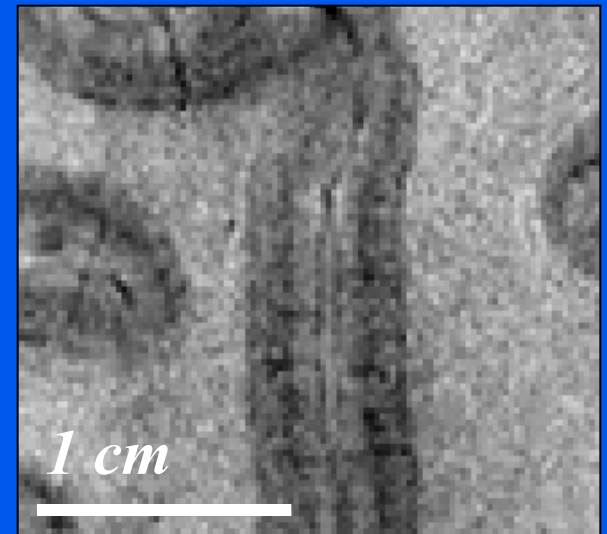
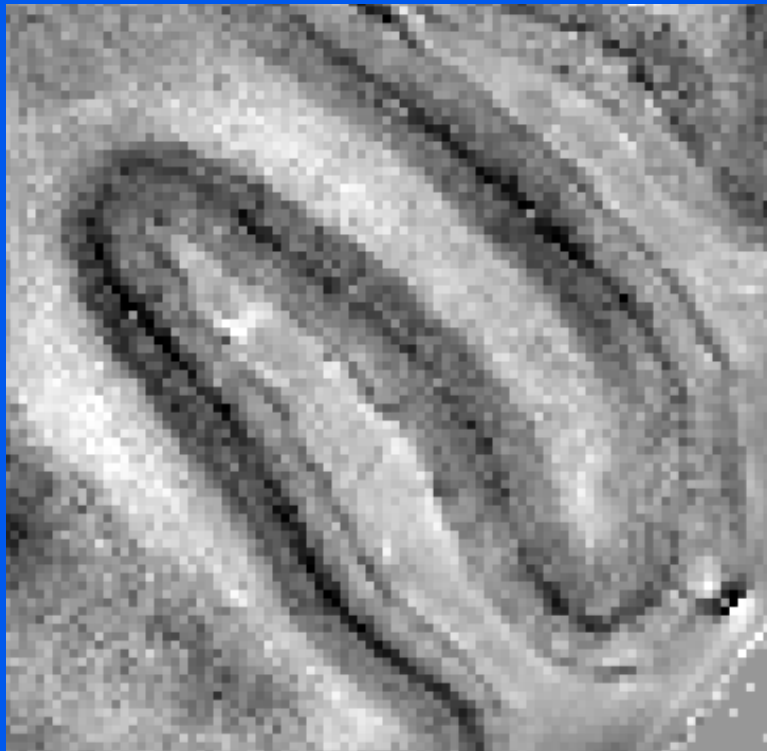


-5 Hz

5 Hz

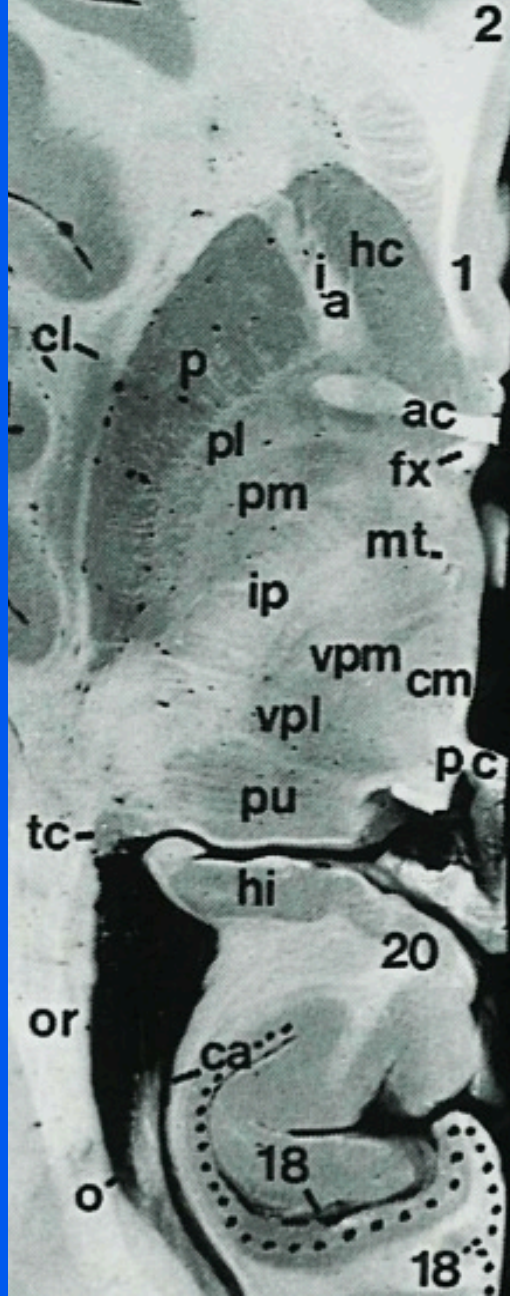
intra-cortical frequency contrast

-5 Hz 5 Hz

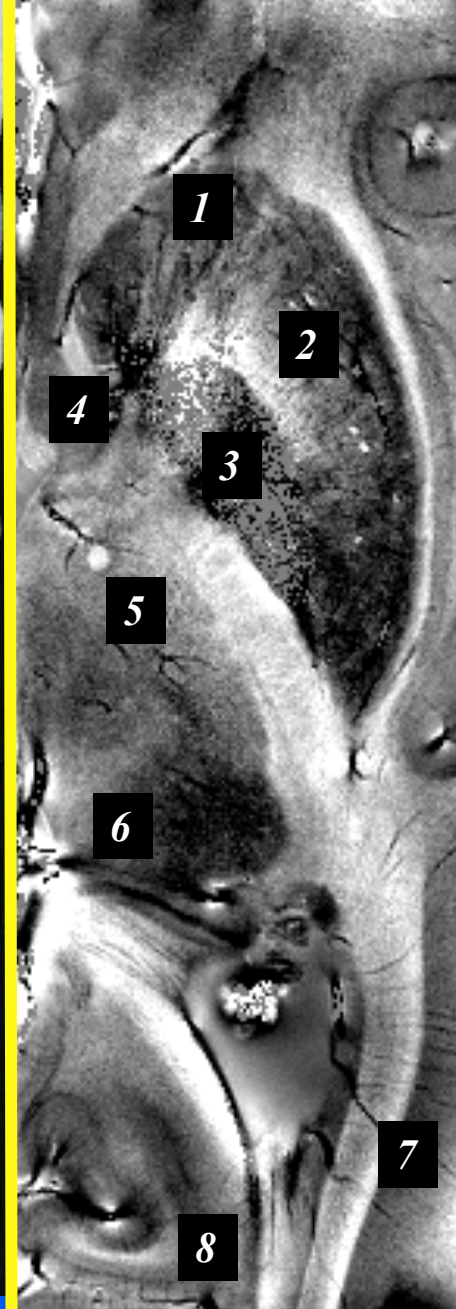


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Duvernoy

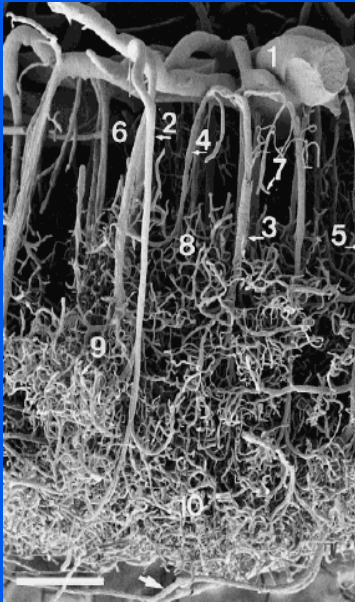


MRI phase

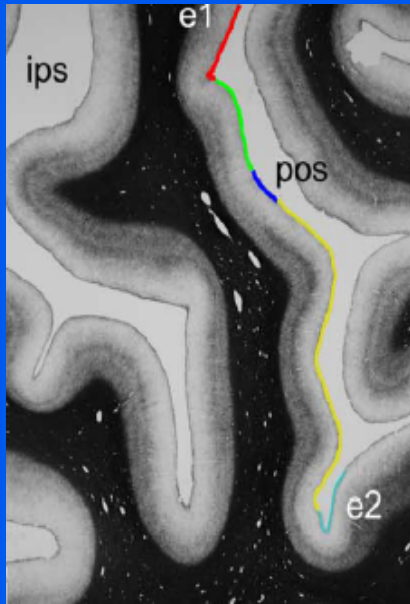
frequency reflects anatomy

1. *head of the caudate nucleus;*
2. *putamen;*
3. *globus pallidus*
4. *anterior column, fornix;*
5. *cross-section of the
mamillothalamic tract;*
6. *pulvinar*
7. *veins crossing the optic
radiations;*
8. *line of Gennari*

There are multiple contributors to magnetic properties of brain



**deoxy-
hemoglobin:**
Paramagnetic
(increases field)



myelin (lipids):
Diamagnetic
(decreases field)



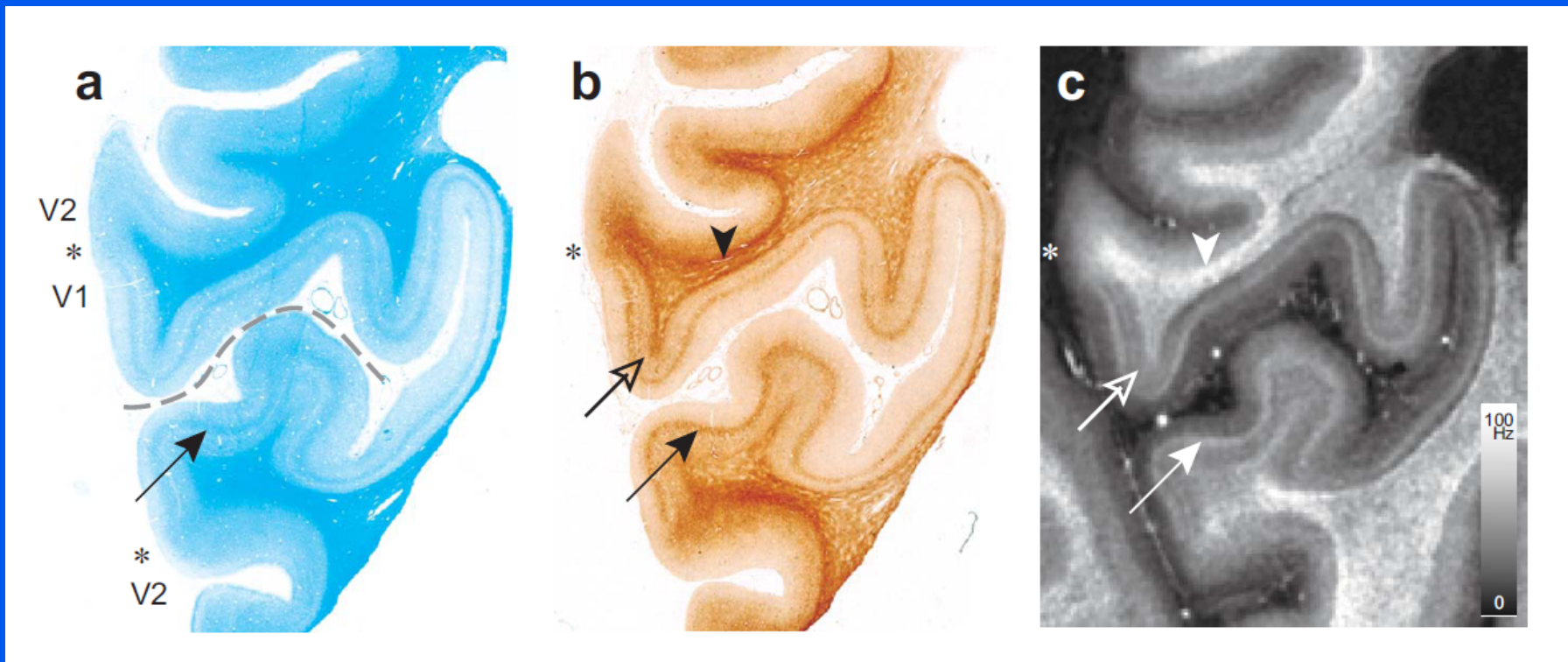
iron (ferritin):
Paramagnetic
(increases field)

Correlative MRI-Histology

myelin

iron

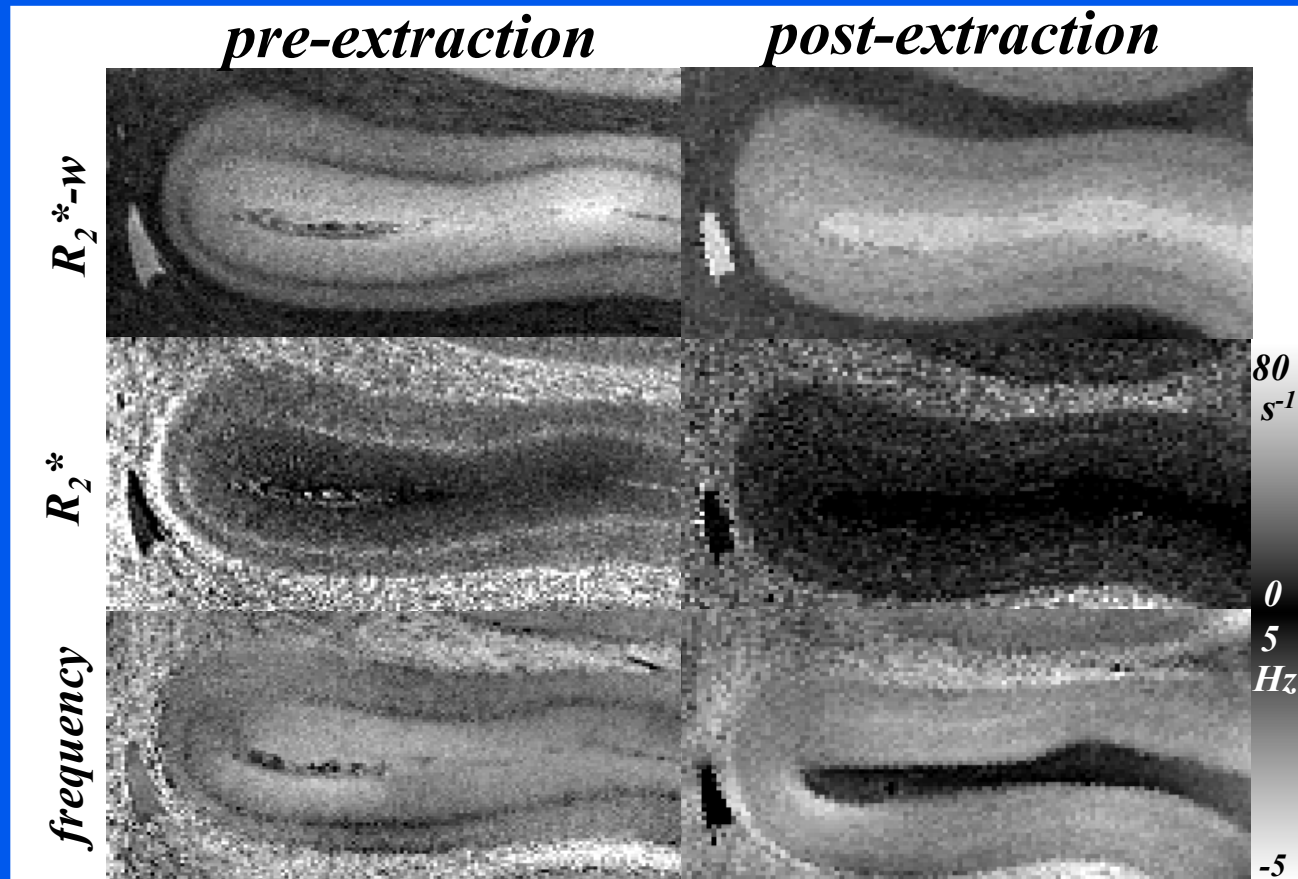
R_2^*



Fukunaga et al PNAS 2010

Cortex

chemical extraction of tissue iron

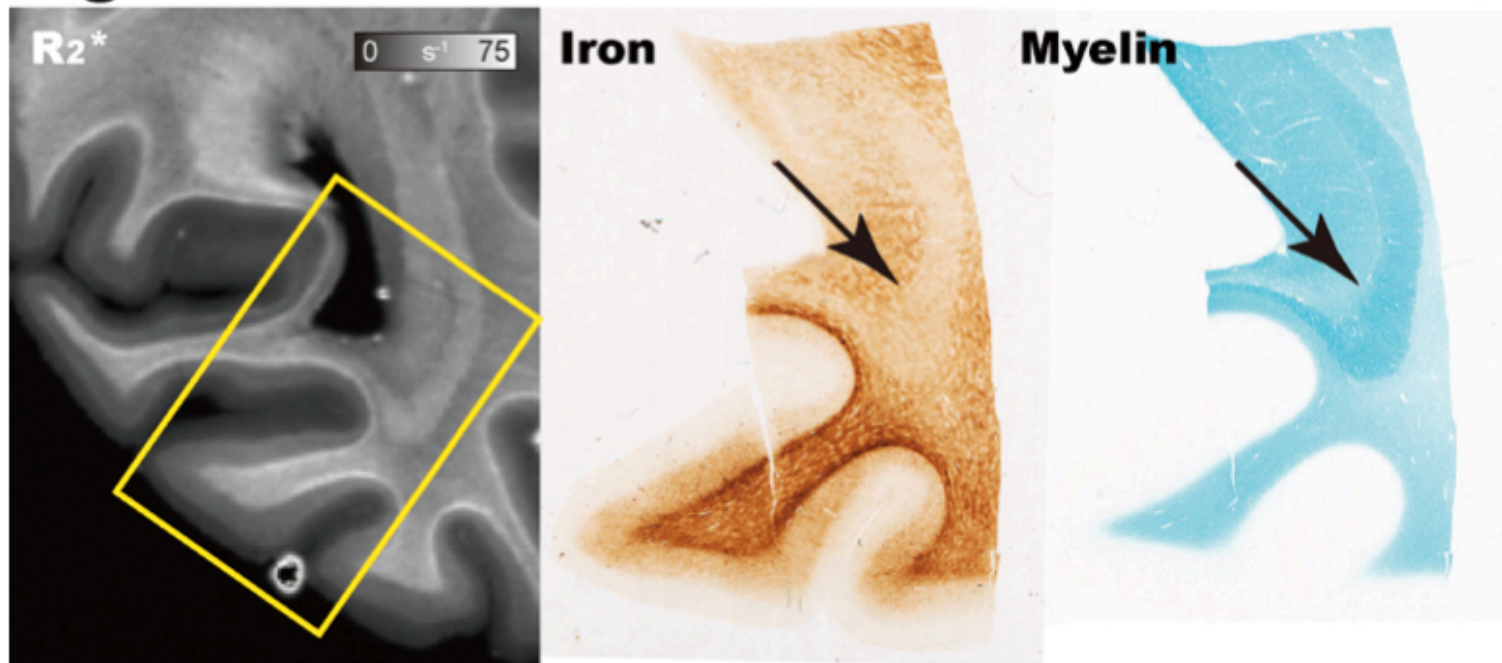


Investigation of magnetic susceptibility contrast across cortical grey matter and white matter

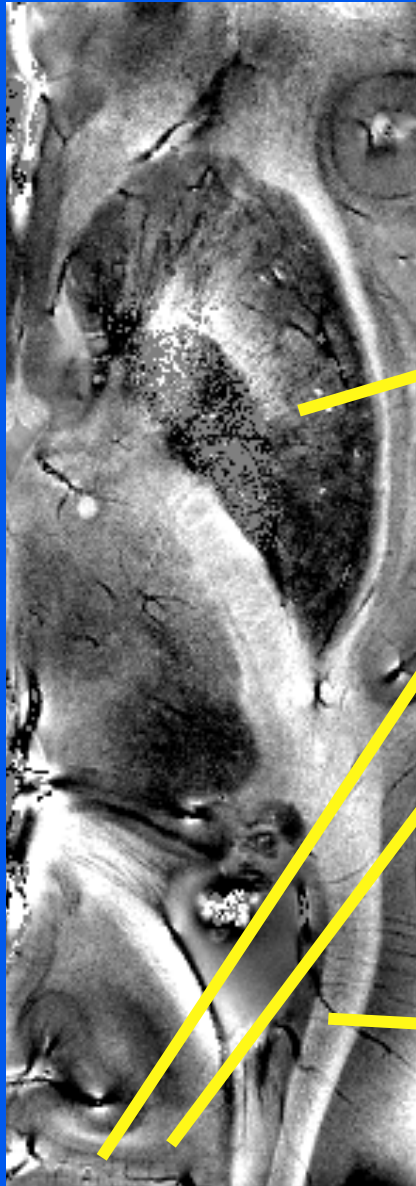
M. Fukunaga^{1,2}, P. van Gelderen¹, J. Lee¹, T-Q. Li¹, J. A. de Zwart¹, H. Merkle¹, K. M. Matsuda³, E. Matsuura⁴, and J. H. Duyn¹

¹Advanced MRI section, LFMI, NINDS, National Institutes of Health, Bethesda, MD, United States, ²Biofunctional Imaging, Immunology Frontier Research Center, Osaka University, Suita, Osaka, Japan, ³Laboratory of Pathology, NCI, National Institutes of Health, Bethesda, MD, United States, ⁴Laboratory of Neuroimmunology, NINDS, National Institutes of Health, Bethesda, MD, United States

Fig. 3

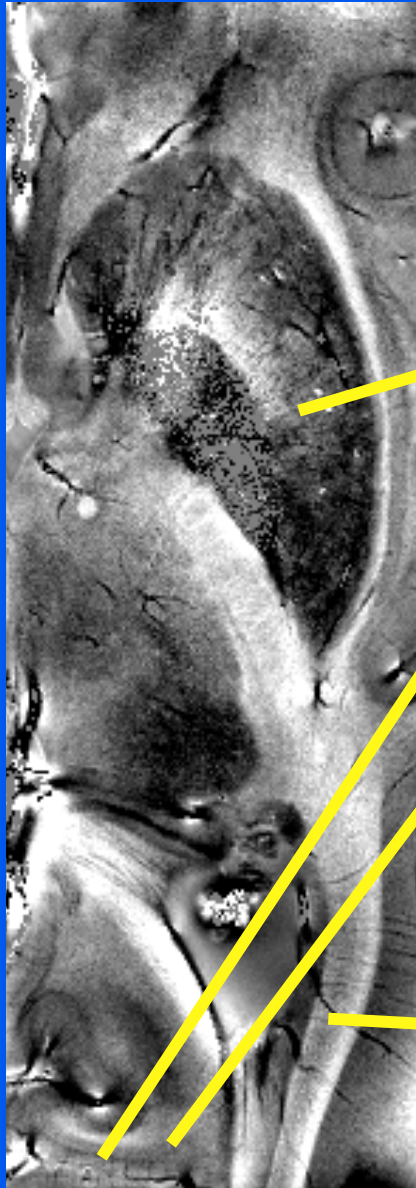


Source of susceptibility contrast in human brain



| Tissue | R_2^* | Frequency | Explanation |
|--|---------------------------------------|--------------------------------------|--|
| Venous Vasculature, Hemorrhages | increased | positive | deoxy-hemoglobin |
| Basal Ganglia, Red Nucleus | increased | positive | iron (ferritin) |
| Cortical layers: infra granular, Gennari, Purkinje | increased | positive | iron (ferritin) |
| Grey versus sub-cortical white matter | variable | generally positive | myelin and iron |
| MS Lesion | variable | variable | myelin, iron, deoxyhemoglobin |
| Fiber bundles | increased <i>if angled with field</i> | negative <i>if angled with field</i> | myelin, <i>microstructure, orientation</i> |

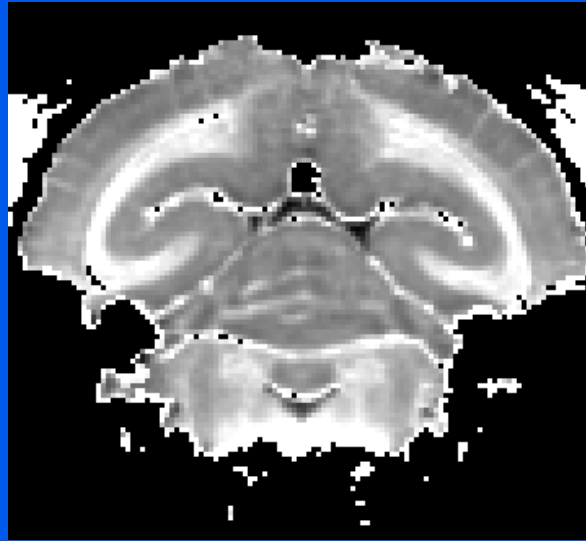
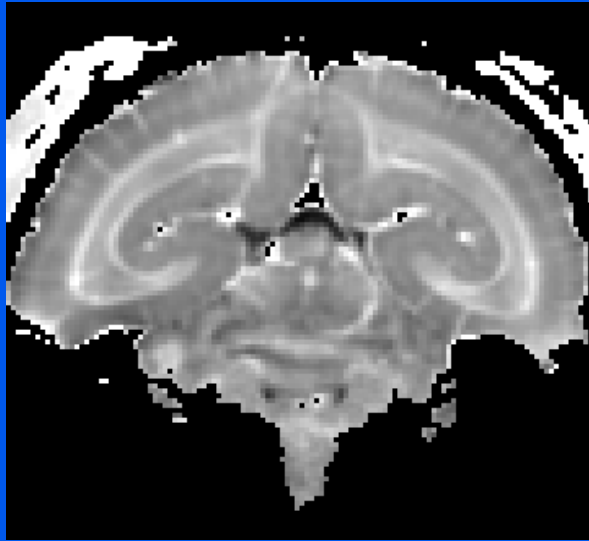
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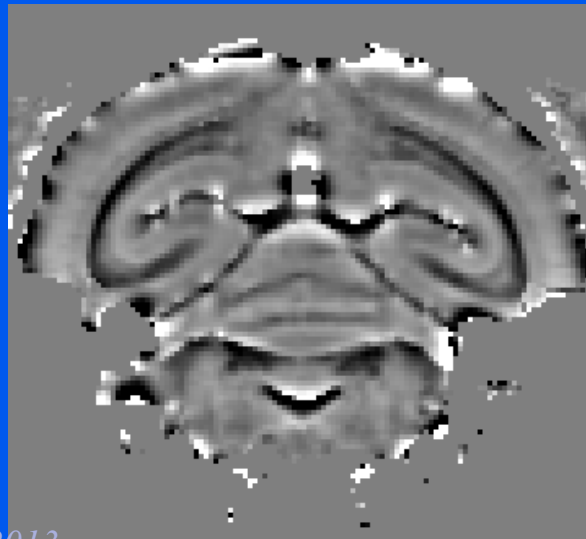
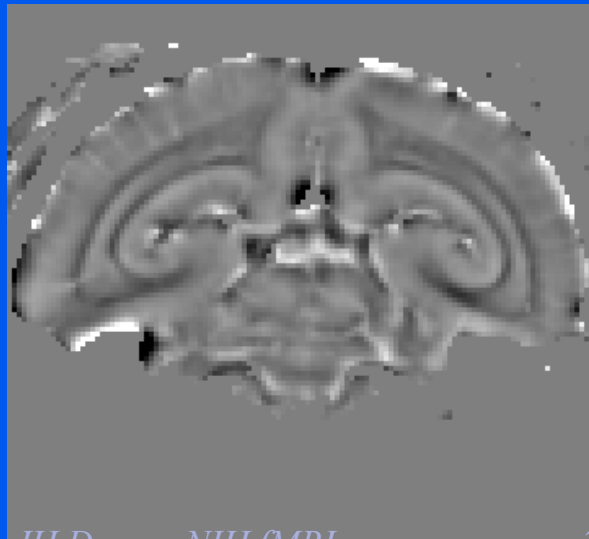
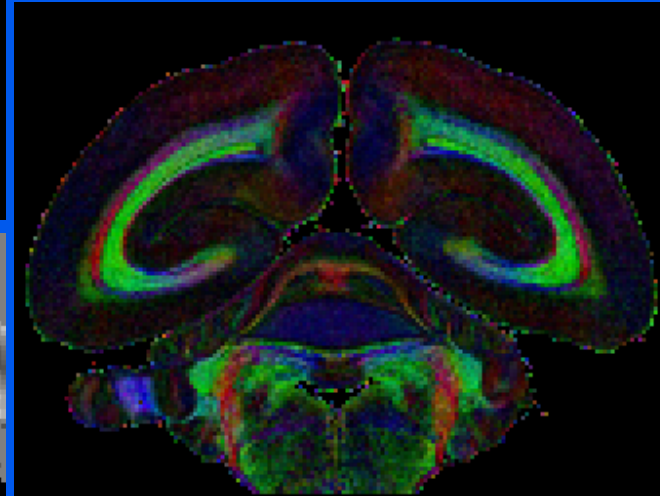
⊙ B_0

↑ B_0



R_2^*

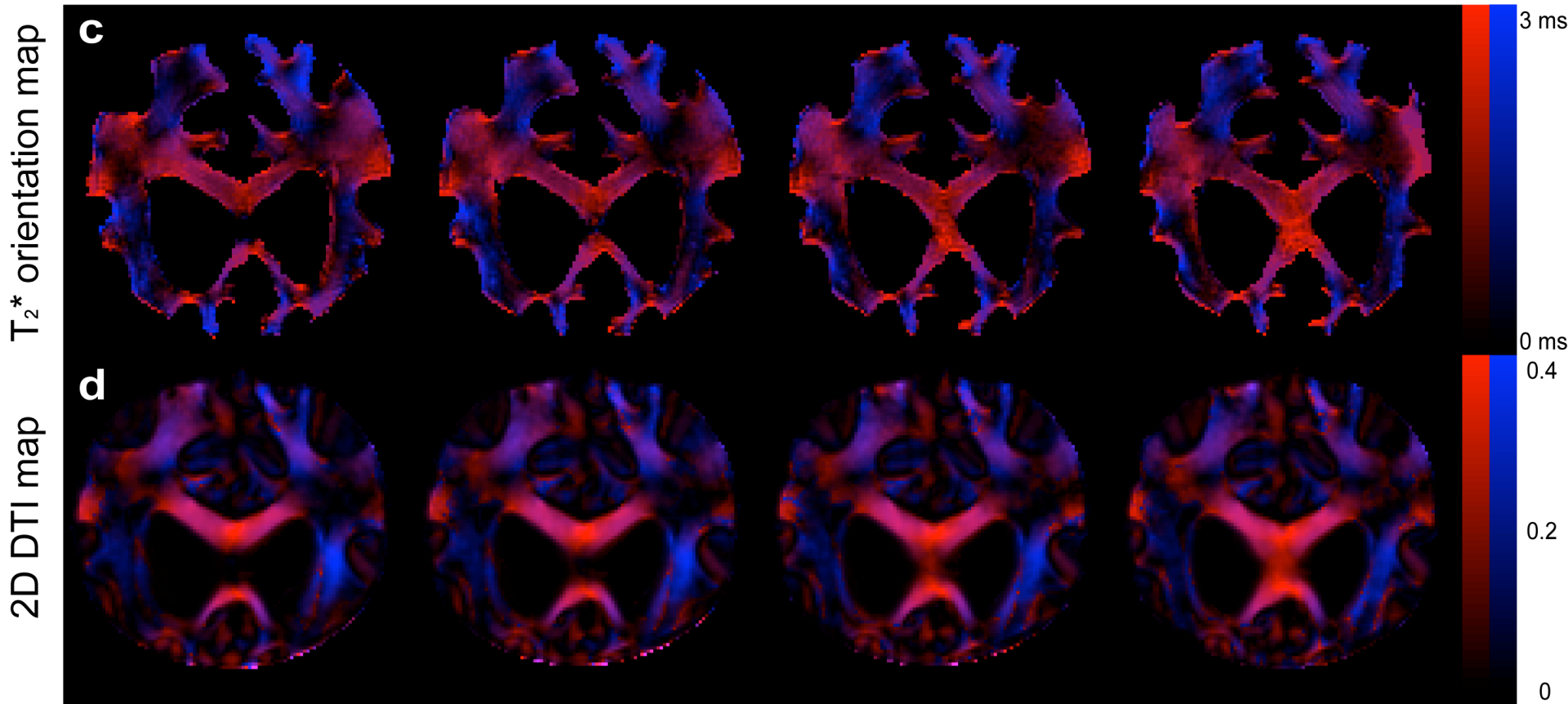
DTI



frequency

Orientation dependence of R_2^*

allows mapping of major fiber bundles

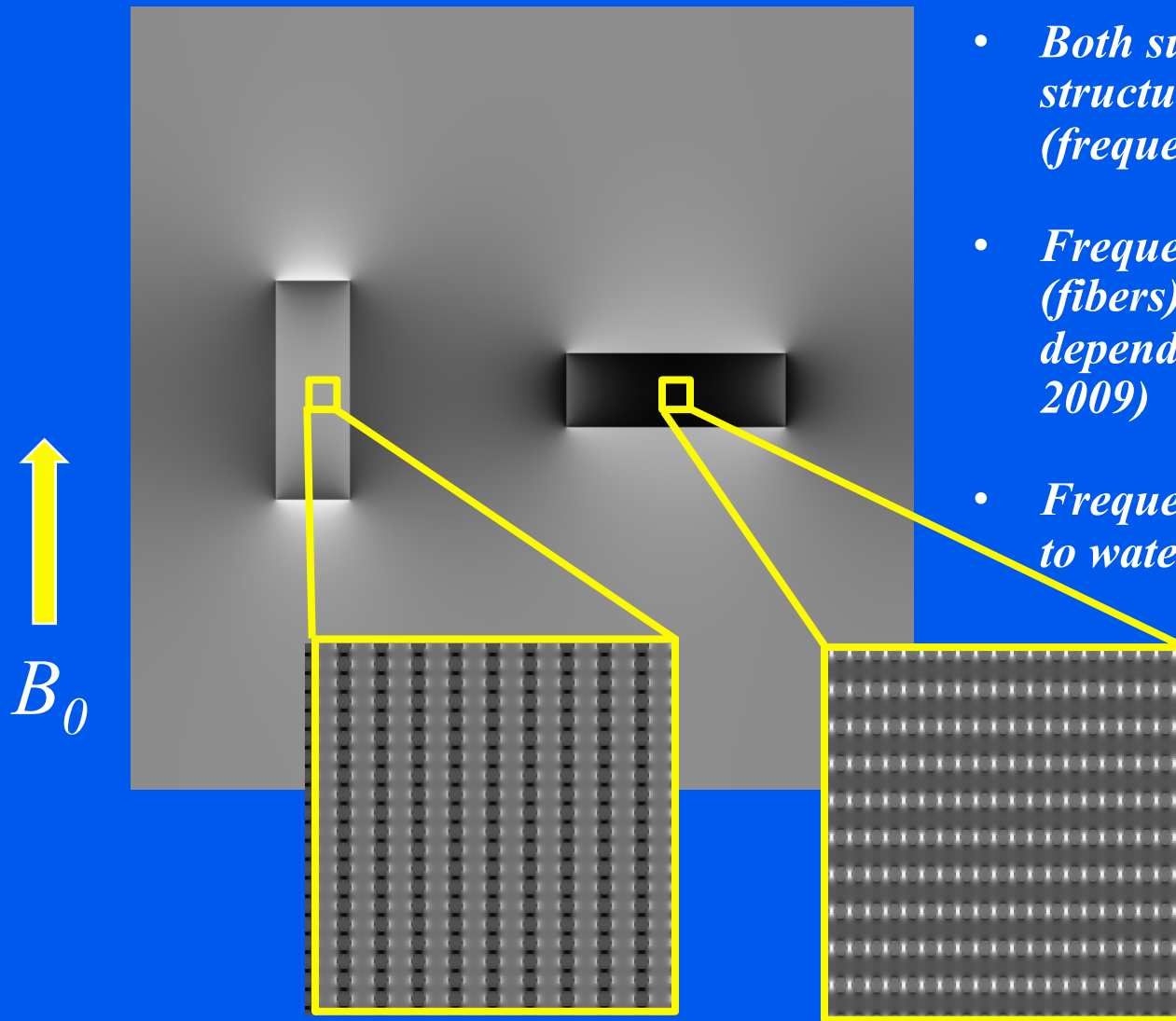


T_2^* -based fiber orientation mapping[☆]

Neuroimage 2011

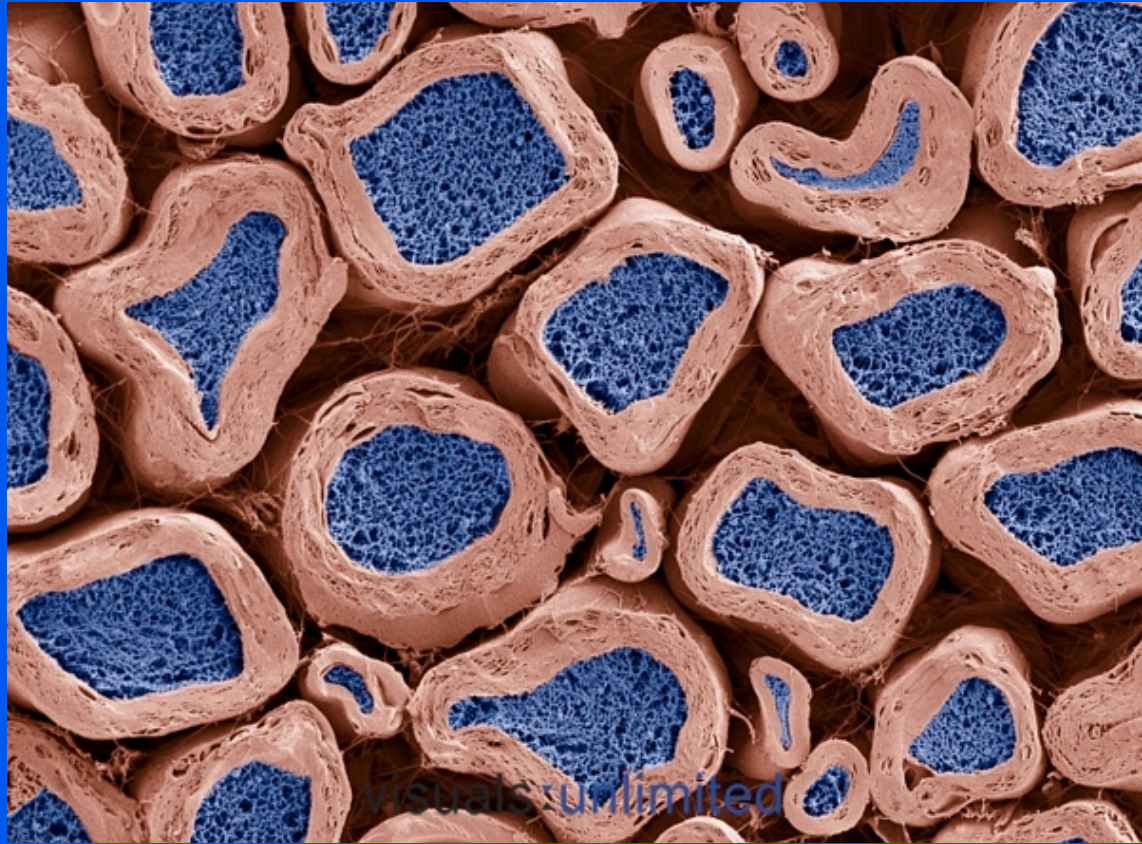
Jongho Lee^{a,b,*}, Peter van Gelderen^a, Li-Wei Kuo^a, Hellmut Merkle^a, Afonso C. Silva^c, Jeff H. Duyn^a

Orientation dependence of R_2^* and frequency

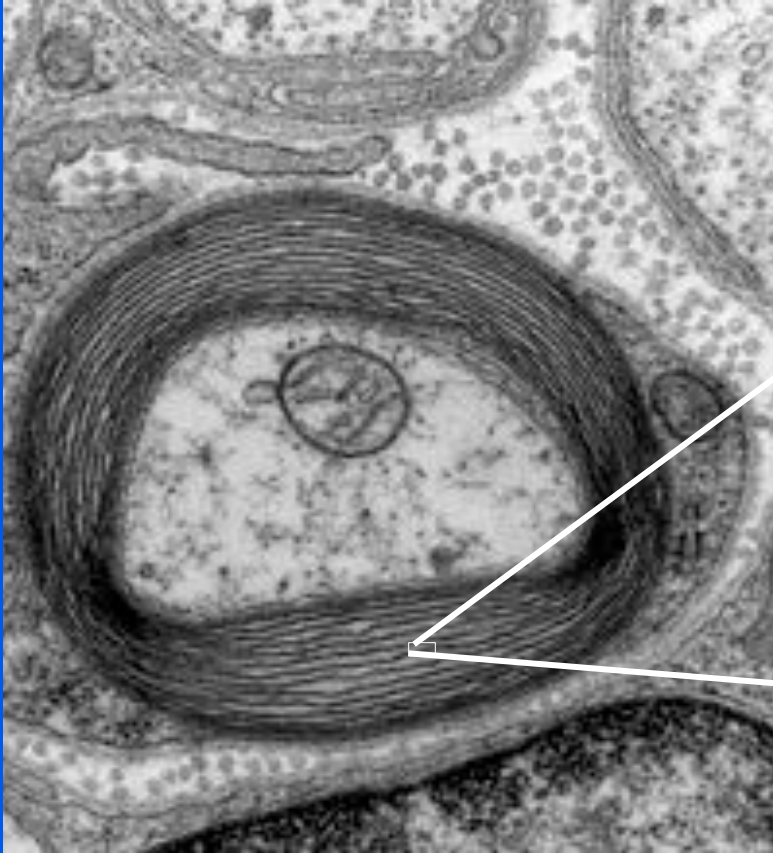


- *Both supra- and sub-voxel scale structure can affect field (frequency) and its variation (R_2^*)*
- *Frequency inside around cylinders (fibers) has approximately $\sin^2 \theta$ dependence (He/Yablonskiy PNAS 2009)*
- *Frequency effect can be partly due to water compartmentalization*

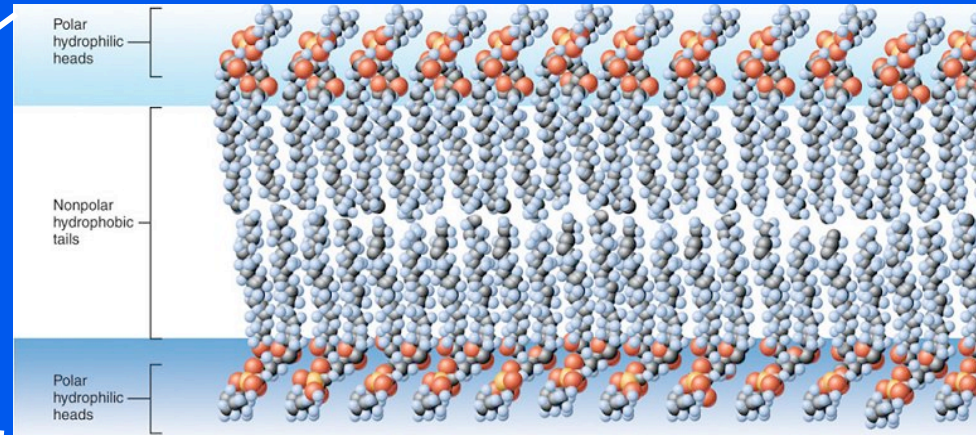
white matter is highly structured at various scales



$2\ \mu m$

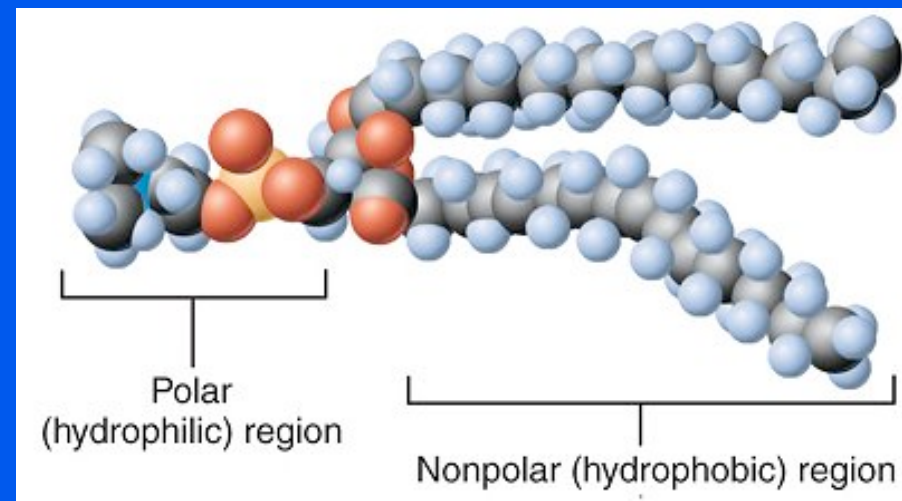


wikipedia.org



2 nanometer

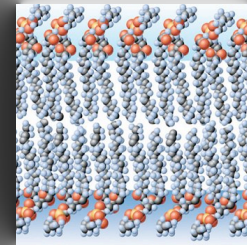
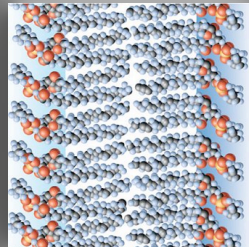
yellowtang.org



susceptibility of myelin sheet is anisotropic

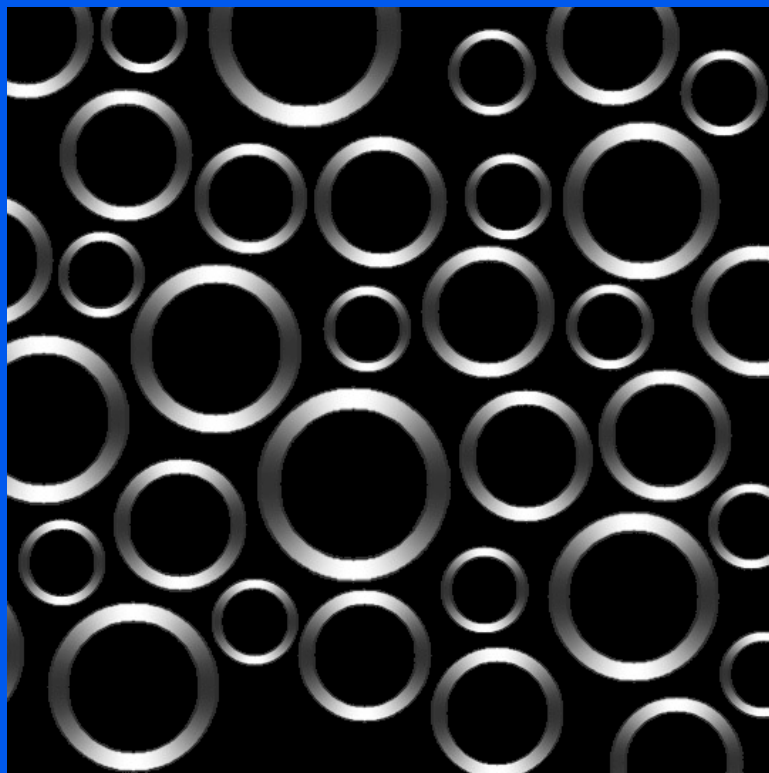


B_0

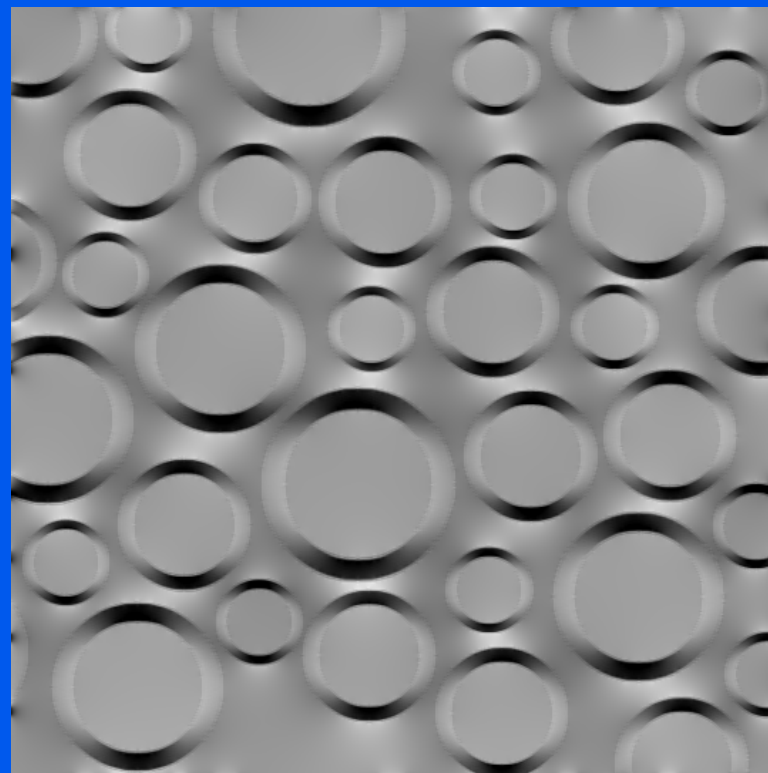




B_0

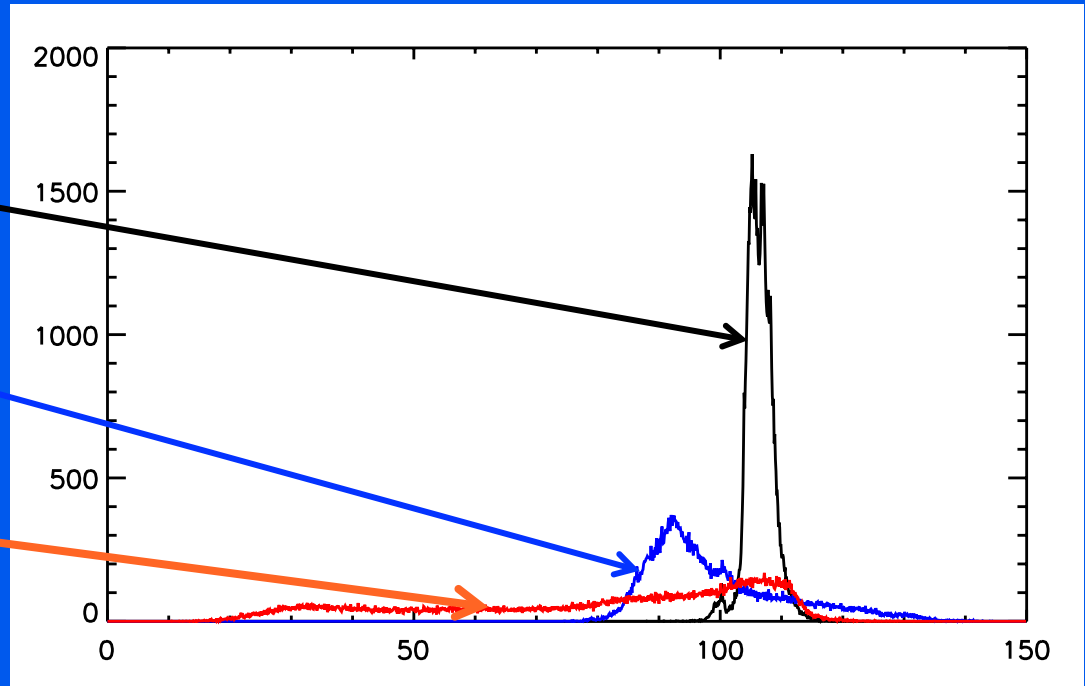
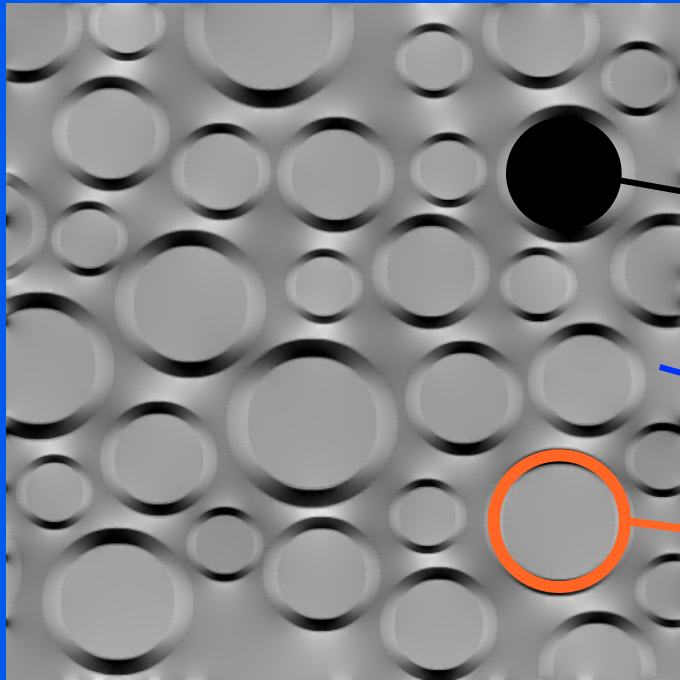


magnetic susceptibility



frequency

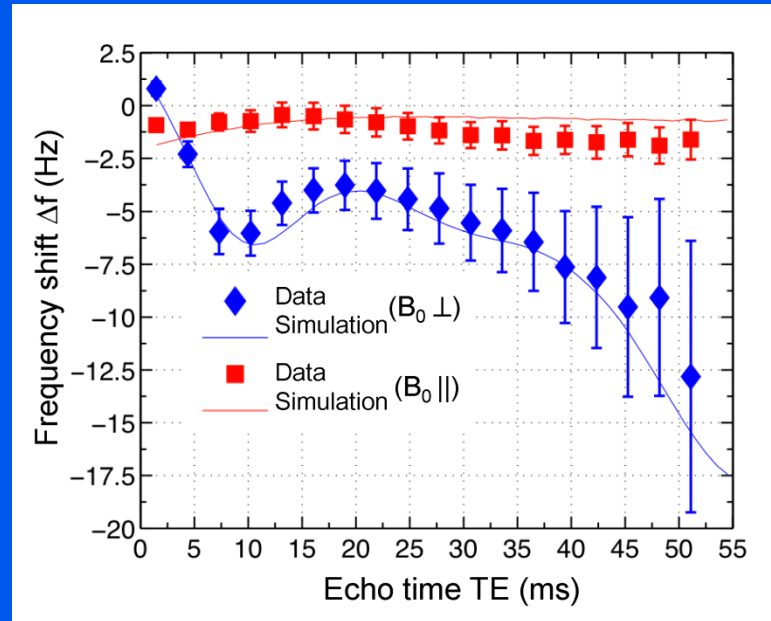
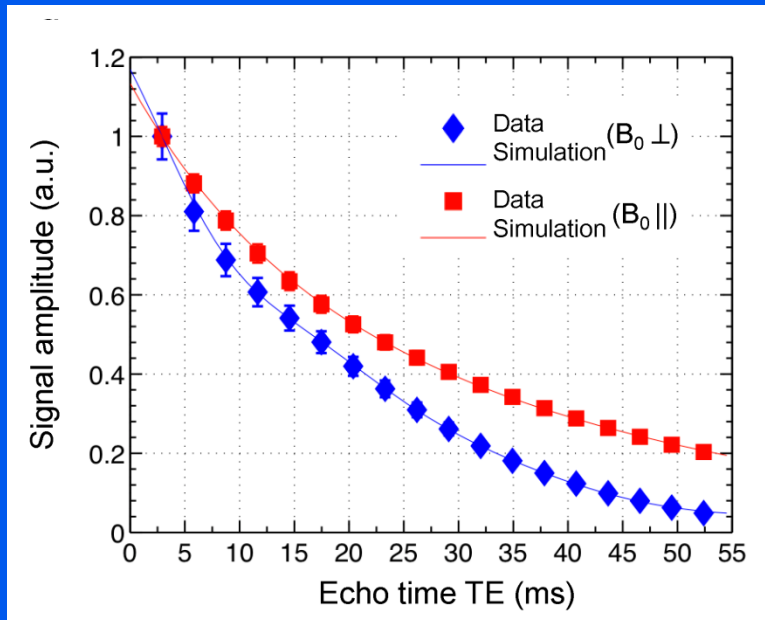
compartment-specific frequency shifts



frequency

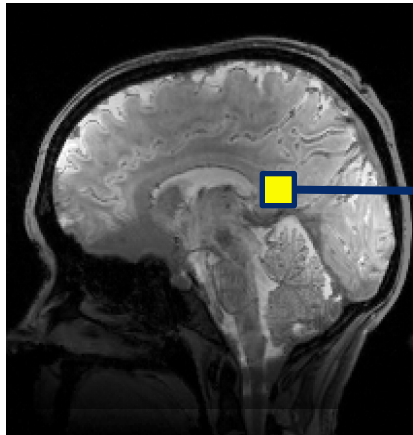
Simulated Signal Decay

comparison with marmoset data

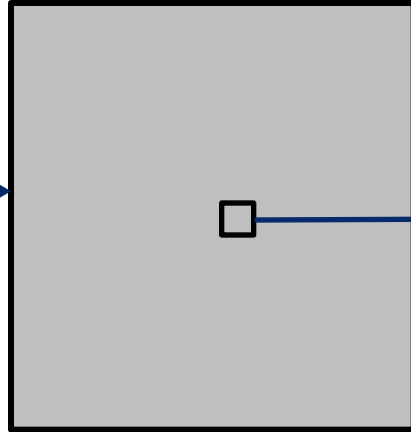


$\chi_{\parallel} - \chi_{\perp} = -0.022 \text{ ppm}$
Supportive of compartmental origin of components!

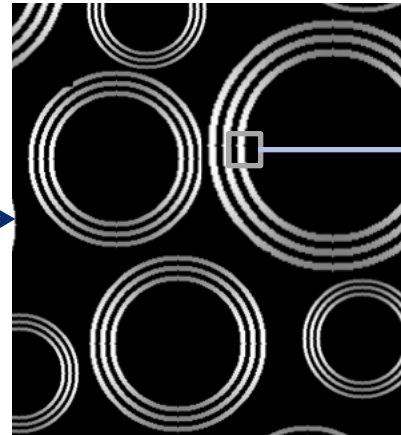
MRI image
 10^{-1} m



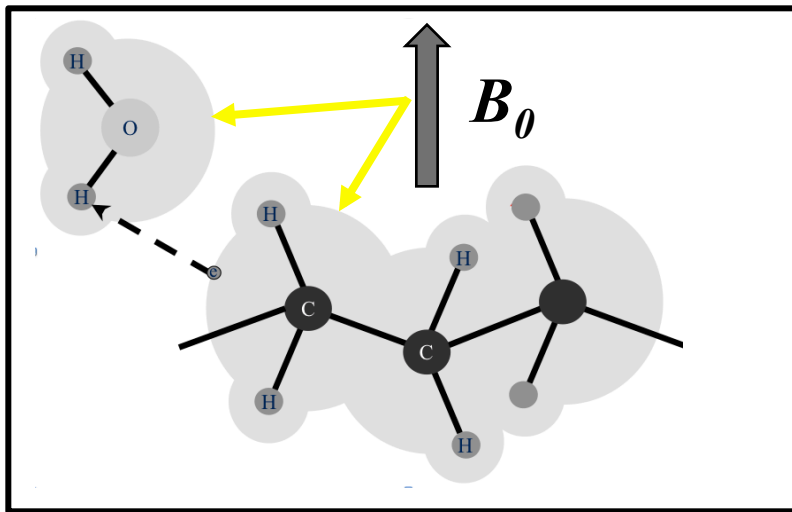
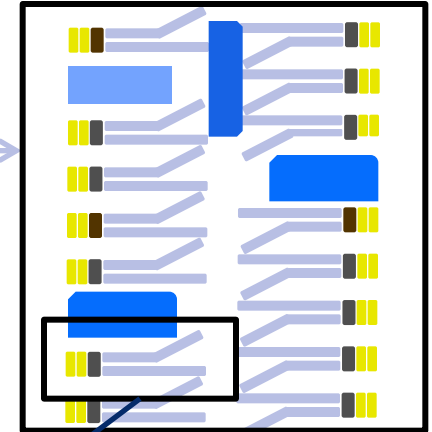
MRI voxel
 10^{-3} m



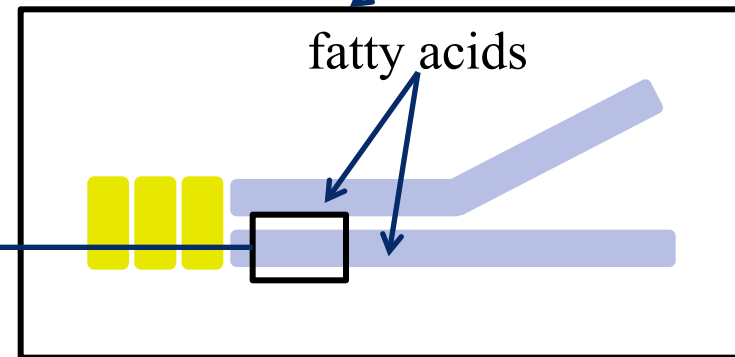
axons
 10^{-5} m



myelin sheath
 10^{-8} m



electron orbits
 $< 10^{-9} \text{ m}$

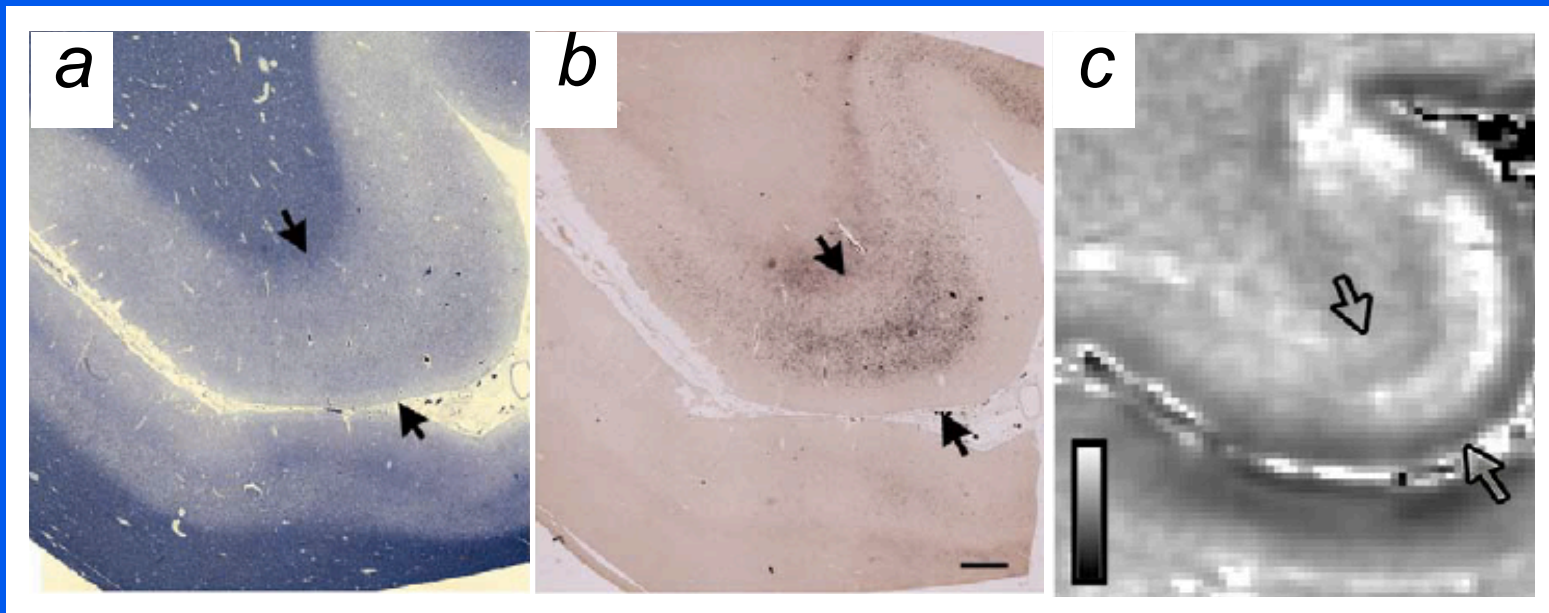
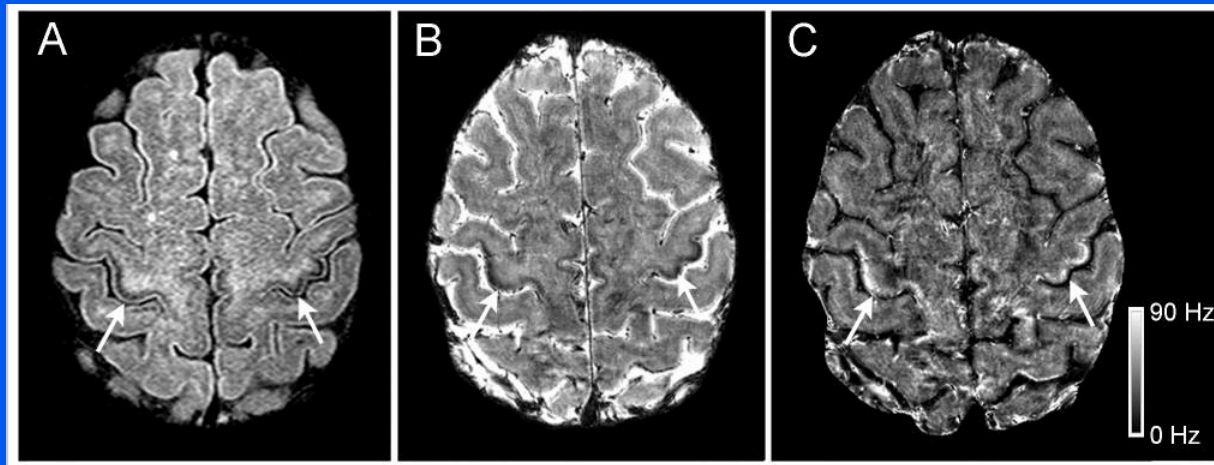


phospholipid molecule
 10^{-9} m

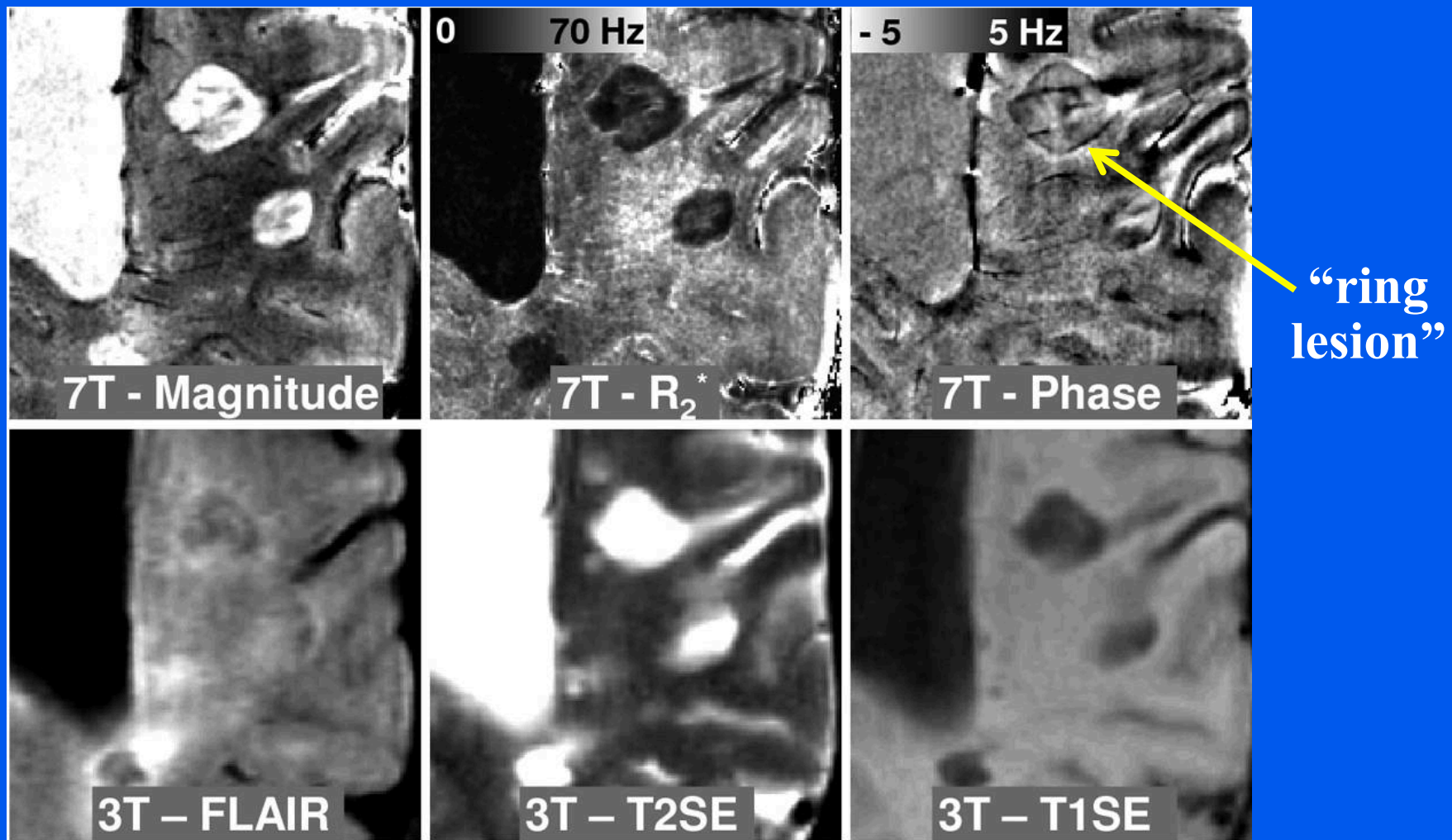
Overview

- *What is magnetic susceptibility contrast?*
- *Observations at high field*
- *Interpretation*
- *Clinical Applications*

Amyotrophic Lateral Sclerosis

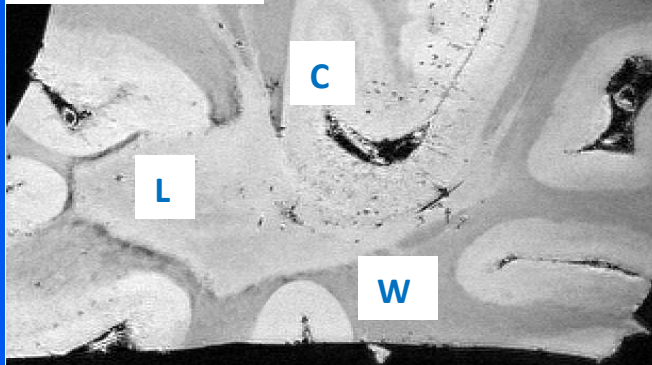


Multiple Sclerosis



Yao et al, Radiology 2012

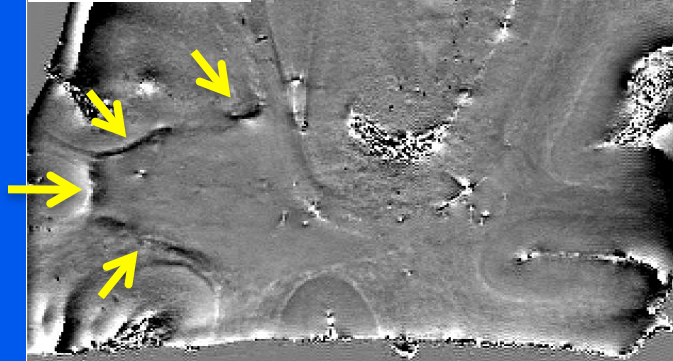
Magnitude



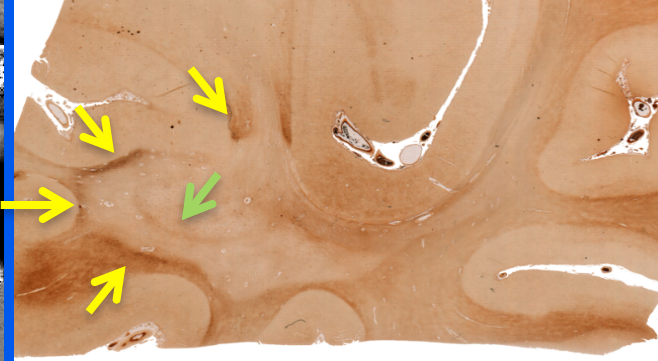
Myelin



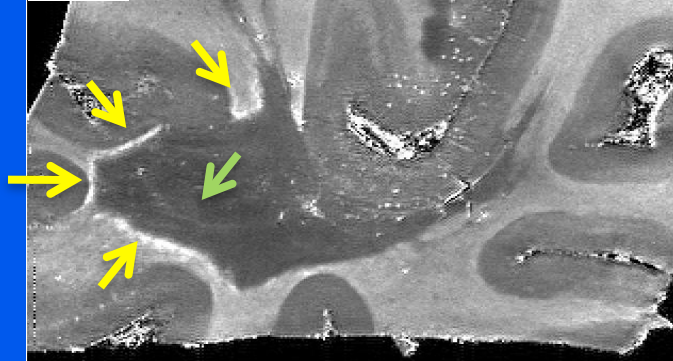
Frequency



Iron



R_2^*



Ferritin

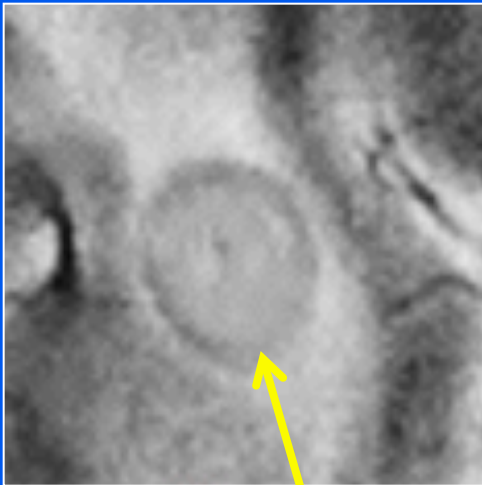


Yao et al , Radiology 2012; Bagnato et al, Brain 2011

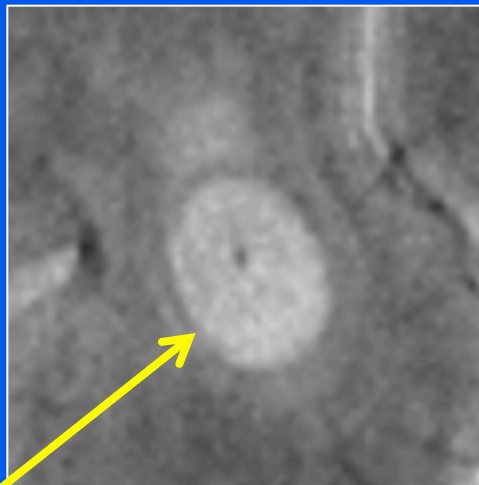
Multiple Sclerosis

subset of “ring lesions” enhance on Gad-MRI

GRE phase



GRE magnitude



Post Gad T₁



Increased frequency and signal loss
at lesion rim

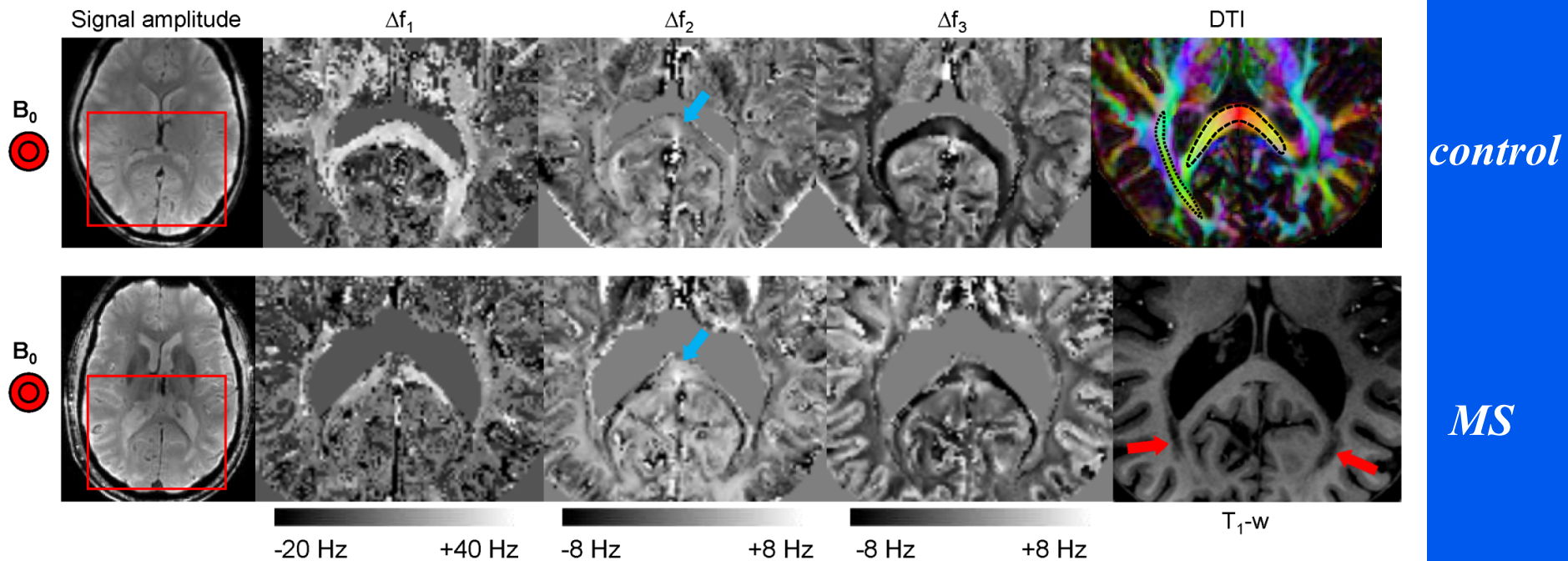
BBB leakage indicating
active disease process

Sati, Reich et al, NINDS

Multi-Component Complex Fitting of GRE Decay Curve

separation of myelin, axonal and interstitial water

$$S = A_1 e^{(-R_1 + i\Delta f_1)t} + A_2 e^{(-R_2 + i\Delta f_2)t} + A_3 e^{(-R_3 + i\Delta f_3)t}$$



Sati et al., Neuroimage 2013

Summary

- *Susceptibility contrast provides rich anatomical contrast in human brain MRI that increases with field strength*
- *Single scan allows one to extract various parameters (and contrasts)*
- *Reports on myelin and iron content*
- *Microstructural compartments have distinct decay characteristics*
- *Potentially allows one to extract micro-structural information*

Recommended reading

- *Duyn et al: PNAS 2007*
- *He/Yablonskiy: PNAS 2009*
- *Wharton/Bowtell: PNAS 2012*
- *Duyn: Journal of Magnetic Resonance 2013*
- *Sati et al: Neuroimage 2013*